ECO-SOCIAL ASSESSMENTS OF AQUATIC ECOSYSTEMS

VOLUME 1: LIBRARY OF GENERIC RELATIONSHIPS FOR SADC RIVERS AND ESTUARIES

H Bukhari, C Brown, L van Niekerk, H van Deventer, A Joubert, S Taljaard, L Goso, K Reinecke, C Hansen, L Smith-Adao, J Adams, S Lamberth, S Weerts, D Lemley, J King

TT 934/1/23

AFRICA'S LIVING RIVERS PROGRAMME

ECO-SOCIAL ASSESSMENTS OF AQUATIC ECOSYSTEMS

VOLUME 1: LIBRARY OF GENERIC RELATIONSHIPS FOR SADC RIVERS AND ESTUARIES

Report to the
WATER RESEARCH COMMISSION

by

H Bukhari, C Brown, L van Niekerk, H van Deventer, A Joubert, S Taljaard, L Goso, K Reinecke, C Hansen, L Smith-Adao, J Adams, S Lamberth, S Weerts, D Lemley, J King

WRC Report No. TT 934/1/23

March 2024

Obtainable from
Water Research Commission
Bloukrans Building, Lynnwood Bridge Office Park
4 Daventry Street
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

This is the final report of Water Research Commission project no. C2020/2021-00437
Project Leader: CA Brown

The outcomes of this report are published in two volumes, namely:
Volume 1: Library of Generic Relationships for SADC Rivers and Estuaries (this report)
Volume 2: Notes for Using Generic Relationships in Drift (WRC Report No. TT 934/2/23)

ISBN 978-0-6392-0591-5

Suggested citation

Bukhari H, Brown C, van Niekerk L, van Deventer H, Joubert A, Taljaard S, Goso L, Reinecke K, Hansen C, Smith-Adao L, Adams J, Lamberth S, Weerts S, Lemley D, King J (2024) Eco-Social Assessments of Aquatic Ecosystems, Volume 1: Library of Generic Relationships for SADC Rivers and Estuaries. Africa's Living Rivers Programme (WRC Report No. TT 934/1/23). Water Research Commission, Pretoria.

EXECUTIVE SUMMARY

Executed as part of Africa's Living Rivers Programme, Eco-Social Assessments of Aquatic Ecosystems funded by the South African Water Research Commission (Contract #: C2020-00437).

The project started in April 2021 and ended in February 2024.

Rationale

Three decades ago, South Africa began to support an ecosystem approach to water management, long before the term had been coined or the country's law required it. The approach has matured enormously, with several major advances and important consolidation activities funded by the Water Research Commission. Basin-wide modelling of the ecological and social implications of planned water-resource planning and management across Africa and Asia has provided massive, basin-specific DRIFT-Water databases. A much smaller but growing set of data describes the drivers of land-use change and the ecological and social responders (DRIFT-Land).

The progress made is mirrored in advances in South Africa's Estuarine Method for calculating Environmental Flows, which has its own array of databases.

Both methods/models are ecosystem-based approaches. They address the social and ecological implications of changes in water flow, water quality, sediment flow, land use and in-channel infrastructure. They, and similar initiatives, are increasingly being used to underpin decision-making and reporting in other areas of basin management, such as planning and evaluating restoration initiatives; ecosystem services quantification and valuation; and compliance reporting on sustainability targets, such as the SDGs, Africa Agenda 2063, and other international conventions and targets, e.g. Biodiversity Convention, RAMSAR, WASH. They also contribute towards climate resilience by predicting the potential climate-driven changes in river ecosystems, allowing time to make the necessary adjustments to deal with them.

These databases contain knowledge needed to improve our understating and management of river and estuarine ecosystems. This project was a first step in collating that knowledge into formats that are more readily accessible to managers and decision makers in the form of generic sets of indicators, response curves and their links driving ecosystem functioning and hence response to human interventions.

Objectives

The main objective of Contract #: C2020-00437 was to develop a set of indicators, links and generic response curves that depict the relationships between physical-chemical-biological drivers and ecological-social responses in southern African rivers and estuaries. The idea being that the indicators, links and generic curves can be used to set up a coarse-level DRIFT (Downstream Response to Imposed Flow Transformations) Eco-social Model for most major river basins in the Southern African Development Community (SADC) for which daily hydrological time series are available at a fraction of the time and expense of set up the model from scratch. Once set up, the DRIFT Eco-social Model can be used to provide first-level predictions of the ecological and social implications of changes in the flow of water and sediment for the rivers and estuary in the basin.

Other project aims included:

- To develop an improved understanding on the uses and opportunities for use of the kinds of information generated by ecosystem-based approaches, such as DRIFT and the South Africa's Estuarine Method, for calculating EFlows.
- To group major rivers and estuaries in SADC into a range of functional types to facilitate the development of generic relationships.
- To build capacity through supervision of South African and SADC postgraduate students.
- To contribute towards WRC's visions to be a global water knowledge node and South Africa's premier water knowledge hub active across the entire water innovation value chain.

Methodology

The project was arranged in eight tasks. The tasks and the methods applied in each are summarised below.

Task	**Activities**
Review of the use of ecosystem-based information in DSSs for SADC River Basin Organisations	The review was organised as a paper and published: BUKHARI H and BROWN C (2022) A comparative review of decision support tools routinely used by selected transboundary River Basin Organisations. *African Journal of Aquatic Sciences* **47** (3) 318-337. DOI: 10.2989/16085914.2021.1976610.
Review the use of ecosystem-based EFlows assessment outputs for global and national reporting processes	The review was conducted from two perspectives: 1. How can EFlows assessments and EFlows-related outputs for rivers, wetlands and estuaries be used to address data gaps in global and national reporting processes? 2. How can the key global reporting processes, using the Sustainable Development Goals indicators as framework, be used as an evaluation framework at the water basin /management area scale?
Complete a typology of major SADC rivers	Rivers of stream order ≥5 were classified using: ○ 10 Major Habitat Types (MHT) ○ Four slope classes (after Nel *et al.* 2004), overlaid with flats and gorges determined using terrain slope.
Complete a typology of major SADC estuaries	Estuaries of stream order ≥6 were classified using: ○ Biogeographical regions ○ Tidal ranges ○ Functional type.

Task	**Activities**
Develop generic indicators, links and response curves for SADC rivers	DRIFT response curves from eleven DRIFT databases were mined. Indicator and link selection, and response curves shape and size were fairly consistent across a wide range of river types. However, they differed across floodplains, wetlands and lakes.
Develop generic indicators, links and response curves for SADC estuaries	The process for developing estuarine indicators and response curves differed from that for rivers as there were no existing DRIFT datasets for SADC estuaries. Thus, the South African estuarine specialists set up a DRIFT database for the Pungwe Estuary as part of a project for Global Water Partnership SA. This allowed the specialists to 1) develop an understanding of the DRIFT process and 2) assess the feasibility of converting the South African method used for estuarine EFlows assessment indicators, links and response curves.
Review and test generic indicators, links and response curves	The generic indicators, links and response curves were developed and tested as part of EFlows assessments in (Section 5): ○ The Limpopo Water Management Area ○ The Pungwe River Basin. The generic indicators, links and response curves for individual disciplines were also peer reviewed by selected specialists.
Links to co-funded activities	These included liaison with SADC and other governance structures, a series of related academic and professional presentations, and academic papers and reports.

Results

The project yielded the following main results:

- A comparative review of decision support tools routinely used by selected transboundary River Basin Organisations
- A typology of major SADC rivers (in prep as a paper)
- A typology of major SADC estuaries
- For SADC rivers:
  - 60 generic indicators
  - 226 links and response curves with referenced explanations
- For SADC estuaries:
  - 28 generic indicators
  - 141 links and response curves with referenced explanations
- Notes for using the generic indicators and relationships in DRIFT
- A DRIFT database set up using the generic indicators, links and response curves for rivers

Conclusions

The library of generic indicators, links and response curves summarises nearly three decades of knowledge from leading river- and estuarine specialists on the functioning of southern African rivers. It can be used for rapid tools that are ideal for application in for Africa’s data-limited environment. It can also be used as a template to test and evaluate the relationship used to guide river basin development and management, through post-graduate studies and other focussed research. More than 50 years after the start of EFlows science, the vast majority of models and other applications used to predict changes in river and estuaries ecosystems in response to changes in the flow of their waters and sediments are still reliant on expert opinion for indicators and response curves. This despite the construction of hundreds of dams on river over that period, each one of which provided an opportunity to test these relationships and improve the predictive capacity of the models. With one or two notable exceptions, funding has not been available to monitor the changes wrought by these structures, and hence the numerous opportunities to improve the science of EFlows have largely been ignored.

Key recommendations for future research from the project are:

- Promote the use of ecosystem-based understanding, data and models in managing and developing river basins in southern Africa, in particular transboundary river basins.
- Promote, support and implement monitoring of real-life situations to validate and refine the understanding of how river sand estuary ecosystems react to changes in the flow of water and sediments linked with, *inter alia*, catchment activities, water-resource development and climate change.
- Promote and support the development of long-term data sets, such as hydrology, river planform, estuary bathymetry, fluvial sediment loads and vegetation cover for rivers and estuaries.
- Promote and support *in situ* field measurements and laboratory studies to refine the driver-response relationships, particularly for vegetation, invertebrates and fish.
- Refine ecosystem typology through ground-truthing
- Promote the use of methods of assessment that enhance understanding of ecosystems rather than “black-box” methods that provide convenient but limited and often flawed answers and do not promote understanding of how and why these ecosystems function.
- When applied, if the curves are adjusted based on data, literature or expert opinion, these changes should be documented in an ongoing process to create a centralised repository of information on how and why river and estuarine ecosystems respond the way they do to human intervention.
- Future development should include generating methods for translating hydrology into ‘generic’ hydraulic indicators. This would also facilitate the expansion of the library to include wetlands and floodplains.

ACKNOWLEDGEMENTS

The DRIFT databases used in this project were compiled by specialists who referenced the scientific literature, where available and applicable. The scientific literature is cited in the explanations provided but, for the most part, the databases and reports accompanying them are unpublished and, in many cases, are not generally available, which makes it difficult to cite the specialists. Thus, by way of acknowledgement, the specialists that contributed their knowledge and understanding to the DRIFT databases are (in no particular order): Dr Andrew Birkhead, Dr Casper Bonyongo, Prof. Cate Brown, Dr Alison Joubert, Dr Barry Clark, Dr Marc Cloutier, Ms Adjany Costa, Prof. Ian Cowx, Mr Colin Christian, Dr Barbara Curtis, Mr Paulo Emilio, Dr Justine Ewart-Smith, Ms Katherine Forsythe, Mr Amândio Gomes, Dr Pete Hancock, Mr Nick Huckzermeyer, Dr Jackie King, Dr George Krallis, Dr Lois Koehnken, Ms Filomena Livramento, Dr James MacKenzie, Dr Heather Malan, Dr Victor Mamonokene, Dr Gary Marneweck, Mr Wellington Masamba, Mr Miguel Morais, Dr Belda Mosepele, Dr Keta Mosepele, Ms Shishani Nakanwe, Ms Charone Okombi, Ms Cynthia Ortmann, Ms Maria Pereira, Dr Bruce Paxton, Dr Mark Paxton, Mr Freedom Poaty-Ngo, Dr Johannes Rall, Dr Karl Reinecke, Ms Naomi Richardson, Dr Kevin Roberts, Dr Evan Dollar, Dr Jane Turpie, Dr Barry Clarke, Mr Nico Rossouw, Mr Vladimir Russo, Mr Mark Rountree, Prof. Kate Rowntree, Ms Carmen Santos, Ms Adhishri Singh, Dr Paul Skelton, Mr Tim Smith, Ms Sylvie Sougavinski, Dr Helder de Andrade e Sousa, Mr Anton Sparks, Dr Jørn Stave, Dr Susan Taljaard, Dr Ricky Taylor, Dr Toriso Tlou, Ms Coleen Todd, Dr Christa Thirion, Mr James Tsilane, Mr Denis Tweddle, Ms Vuyani Tshabalala-Monyake, Dr Ben van der Waal, Mr Steven Weerts, Dr Armel Ibala Zamba, Dr Bennie van der Waal, Dr Mathew Ross, Dr Ed Buchak, Dr Shirely Bethune, Ms Valdie Boukaka, Dr Patsy Scherman, Prof. Lara van Niekerk, Mr Tongai Castilo, Dr Lightone Marufu, Dr Stephen Lamberth, Prof. Tamuka Nhiwatiwa, Mr Ricardo Guta, Mr Roy van Ballegooyen, Prof. Antonio Hoguane, Prof. Susan Taljaard, Prof. Celia Macamo, Prof. Janine Adams. Dr Fiona MacKay, Mr Steven Weerts, Mr Hassan Bukhari, Ms Jessica Hughes, Ms Gwyn Letley and Ms Angelina Jordanova.

We also extend our gratitude to:

- Mr Bonani Madikizela for overseeing the project and chairing the Reference Group committee meetings
- Ms Gerda Kruger for her role in facilitating communication between Southern Waters and the Water Research Commission
- our colleagues in Southern Waters and at the Council for Scientific and Industrial Research for their support
- our colleagues who peer reviewed the generic indicators, links and response curves
- the Reference Group members for their input and review, especially Gordon O'Brien, Lois Koehnken, and Vaqar Zakari for their support and encouragement
- our friend and colleague, Jackie King, for her inspirational leadership over the years.

This page was intentionally left blank

CONTENTS

4 GENERIC INDICATORS, LINKS AND RESPONSE CURVES FOR SADC ESTUARIES ... 125

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

Agg	Aggregate
AJAS	African Journal of Aquatic Science
ALOS	Advanced Land Observation Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BERI	Bioclimatic Ecosystem Resilience Index
CABI	Centre for Agriculture and Bioscience International
CBD	Convention on Biological Diversity
CIA	Cumulative Impact Assessment
CSIR	Council for Scientific and Industrial Research
D	Dry season
DB	Database
DEM	Digital Elevation Model
DRIFT	Downstream Response to Imposed Flow Transformations
DS	Decision support
DSM	Digital Surface Model
DSS	Decision support system
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EFG	Ecosystem functional group
EFlows	Environmental Flows
EIA	Environmental Impact Assessments
ERM	Environmental Resources Management
EU	European Union
F	Flood or wet season
FEOW	Freshwater Ecoregions of the World
FPOM	Fine Particulate Organic Matter
GBF	Global Biodiversity Framework
GEO	Global Environment Outlook
GET	Global Ecosystem Typology
GHG	Greenhouse gas
GIS	Geographic Information Systems
GloRiC	Global River Classification
GRI	Global Reporting Initiative
HPP	Hydropower Project
ICOLLs	Intermittently Closed/Open Lakes and Lagoons
IFC	International Finance Corporation
IOCE	Intermittently Open/Closed Estuary types
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
LF	Lower foothills
LKSC	Lower Kafue River Sub-Catchment
LL	Lowland rivers
MHT	Major Habitat Types
MS	Mountain streams
NBA	National Biodiversity Assessment
NBSAP	National Biodiversity Strategies and Action Plans
NDC	Nationally Determined Contributions
NFEPA	National Freshwater Ecosystem Priority Areas
OECMs	Other effective area-based conservation measures

OKACOM	Okavango River Basin Water Commission
PAME	Protected Area Management Effectiveness
Q	Discharge
RBO	River Basin Organisation
RDM	Resource Directed Measures
RLE	Red List of Ecosystems
RMETT	Ramsar Management Effectiveness Tracking Tool
SADC	Southern African Development Community
SAGE	Site-level assessment of governance and equity
SANBI	South African National Biodiversity Institute
SDGs	Sustainable Development Goals
SEA	Strategic Environmental Assessments
SEEA	System of Environmental-Economic Accounting
SNA	System of National Accounts
SRTM	Shuttle Radar Topography Mapper
T1	Transition season 1
T2	Transition season 2
UF	Upper foothills
UN	United Nations
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
UP	University of Pretoria
US	University of Stellenbosch
USAID	United States Agency for International Development
USD	United States Dollars
USGS	United States Geological Survey
WIO	Western Indian Ocean
WIOMSA	Western Indian Ocean Marine Science Association
WMA	Water Management Area
WRC	Water Research Commission
WWF	Worldwide Fund for Nature
WWTW	Wastewater Treatment Works
ZAMWIS	Zambezi Water Resources Information System

1 INTRODUCTION

1.1 Background

Ecosystem approaches address the management of human activities and resource-use based on the best understanding of relevant ecosystems (CBD 2004; Tseliou and Tselepides 2020). Their purpose is to ensure that ecosystem structures and functions, which support all life on Earth, are sustained for the benefit of present and future generations, based on scientific understanding and reasoning (www.biodiversitya-z.org).

Three decades ago, South Africa began to support an ecosystem approach to water management, long before the term had been coined or the Country's law required it. Techniques developed and models built, some funded by the Water Research Commission (WRC), have provided decision makers with holistic predictions of how whole river ecosystems and their dependent socio-economic structures could change, at a time when most countries focused, and still do, on allocating an unjustified nominal minimum flow 'for the river'. The approaches have matured enormously, with several major advances and important consolidation activities funded by the WRC.

Of relevance to this project are the DRIFT (Downstream Response to Imposed Flow Transformations) Eco-social Model (King *et al.* 2003; Brown *et al.* 2013; Joubert *et al.* 2022) that is used to assess Environmental Flows (EFlows) for aquatic ecosystems, and the South Africa's Estuarine Method for calculating EFlows (van Niekerk *et al.* 2019 a and b).

EFlows are describe "*the quantity, timing, and quality of the flow of water, sediment and biota required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems*" (World Bank 2013).

Both methods/models are ecosystem-based approaches. They address the social and ecological implications of changes in water flow, water quality, sediment flow, land use and in-channel infrastructure. They, and similar initiatives, are increasingly being used to underpin decision-making and reporting in other areas of basin management, such as planning and evaluating restoration initiatives; ecosystem services quantification and valuation; and compliance reporting on sustainability targets, such as the Sustainable Development Goals (SDGs), Africa Agenda 2063, and other international conventions and targets, e.g. Biodiversity Convention, RAMSAR, WASH. They also contribute towards climate resilience by predicting the potential climate-driven changes in river ecosystems, allowing time to make the necessary adjustments to deal with them (CRIDF 2017; Tonkin *et al.* 2019).

Basin-wide modelling of the ecological and social implications of planned water-resource planning and management across Africa and Asia using the DRIFT Eco-social Model has provided massive, basin-specific DRIFT databases linking drivers of change in river ecosystems with ecological and social responders. A much smaller but growing set of data describes the drivers of land-use change and the ecological and social responders. The progress made is mirrored in advances in South Africa's Estuarine Method for calculating EFlows, which has its own array of databases.

The DRIFT river model has been included in Decision-Support Systems for many transboundary river basins, such as the Pangani (PBWO/IUCN 2006); Kunene (Southern Waters 2010); Orange-Senqu (CSIR 2013; Adams *et al.* 2016); Okavango (King *et al.* 2014); Neelum-Jhelum (Hagler Bailly 2016); Lower Mekong (MRC 2017; 2018); Zambezi (Southern Waters 2018); Pongola (Brown *et al.* 2018); and many more. Similarly, the estuary method has been applied to over 40% of South Africa's estuaries at various levels of confidence (Van Niekerk *et al.* 2019).

In effect, this is charting a new way globally into water-resource planning, addressing holistically the management of the quality and flow of water, sediments and biota along river systems, and the implications for people; and supporting resolution of difficult questions such as who decides what the future of a river or estuary should be, and whether or not the ecological goal for every system should be the same or should differ depending on societal aspirations for each basin.

The work is now recognised globally and applied widely, particularly in countries in Africa and Asia where further water-resource development and dam building is ongoing. The DRIFT model is often specified by global funders, such as the World Bank and Asian Development Bank, and by global conservation agencies, such as International Union for Conservation of Nature (IUCN) and Worldwide Fund for Nature (WWF). It is endorsed by the Permanent Court of Arbitration in The Hague.

1.2 Africa's Living Rivers Programme

The award of the 2019 Stockholm Water Prize to Dr Jackie King for her work in this field led to an initiative called the Africa's Living Rivers Programme, which comprises six main modules, all aimed at Southern African Development Community (SADC) inland waters and at consolidation of the work of past decades.

Module 1:	Model consolidation. Much of the development of the DRIFT suite of models has been done in consultancy work, apart from some consolidation funding from WRC and Southern Waters, with little chance to stand back and reassess model structure and function. This is now being rectified. DRIFT is coded in Delphi, which is no longer widely used. It is being re-coded in the more accessible and commonly-used language, C#. Its modularity will be increased to improve its user-friendliness, and to make it easier for the global community to access and use the model. As part of the upgrade, the database tables will be replaced with modern alternatives, which were not available when DRIFT was coded. This is necessary because of the need to handle the large databases generated for some basins. The objective is a completely re-coded and upgraded DRIFT Eco-Social Model.
Module 2:	Knowledge capture. This project – see Section 1.3.
Module 3:	Knowledge use. This module recognizes that in parallel to the methods and tools supporting ecosystem-based work, institutional capacity building and other

governance activities have made significant advances in South Africa. The country has much to offer in this respect in terms of lessons learnt, success stories and expertise developed. This experience and the lessons learnt therefrom are being shared via a number of avenues, including scientific papers, consulting projects and reports, contribution of material for Global Water Partnership's MOOC on Governance for Transboundary Water Security, serving on expert advisory panels for Asian Development Bank and Global Water Partnership and on the committee for Western Indian Ocean Marine Science Association.

Modules 4 and 5: Rivers and their people and Awareness. Much planning and management of river systems globally is still based on outdated thinking that sees natural systems as a resource to be used to the limit. The world has to change from a mind-set of exploitation to one of respect for these invaluable assets and careful, balanced management. At every level, from governments to local riparian dwellers, there is a need to create more awareness of the value of inland waters and the tools that can help guide that understanding. At this early stage we plan to support global efforts to do this through the following:

- Promote ecosystem/social modelling as an integral initial input to river basin planning and management across SADC-level structures.
- Promote the extrapolation of local data to regional use for both rivers and estuaries.
- Create a film exploring the history of links between the Luvuvhu River, the Makuleke people, relevant water specialists and SANParks.
- Publicise South Africa's work in this field, through the generation of scientific papers.

Module 6: Capacity building. The organisations in the Africa's Living River Programme are all deeply involved in training and capacity building. While some of this is funded through on-going projects, the programme is mobilising funds to support post-graduate training in ecosystem-based approaches to river basin management and technology transfer of models, techniques and knowledge.

1.3 Knowledge Capture (Module 2)

Africa's Living Rivers Programme Module 2: Knowledge Capture Project was funded by the South African Water Research Commission (Contract #: C2020-00437) and titled Eco-Social Assessments of Aquatic Ecosystems.

The project started in April 2021 and ended in February 2024.

1.3.1 Project aims

The main aim of Contract #: C2020-00437 was to develop a set of indicators, links and generic response curves that depict the relationships between physical-chemical-biological drivers and ecological-social responses in southern African rivers and estuaries. The idea being that the indicators, links and generic curves can be used to set up a coarse-level DRIFT (Downstream Response to Imposed Flow Transformations) Eco-social Model for most major river basins in the SADC for which daily hydrological time series are available at a fraction of the time and expense of set up the model from scratch. Once set up, the DRIFT Eco-social Model can be used to provide first-level predictions of the ecological and social implications of changes in the flow of water and sediment for the rivers and estuary in the basin.

Other project aims included:

- To develop an improved understanding on the uses and opportunities for use of the kinds of information generated in by ecosystem-based approaches such as DRIFT and the South Africa's Estuarine Method for calculating EFlows.
- To group major rivers and estuaries in SADC into a range of functional types to facilitate the development of generic relationships.
- To build capacity through supervision of South African and SADC postgraduate students.
- To contribute towards WRCs visions to be a global water knowledge node and South Africa's premier water knowledge hub active across the entire water innovation value chain.

The project aims were completed successfully.

1.3.2 Project tasks

The project was divided into seven main tasks (Table 1.1).

Table 1.1 The project tasks and the sections dealt with the outcomes of each

Task #	Task name
Task 1	Review of the use of ecosystem-based information in DSSs for SADC River Basin Organisations
Task 2	Review the use of ecosystem-based EFlows assessment outputs for global and national reporting processes
Task 3	Complete a typology of major SADC rivers and estuaries, and a similar analysis for locations of existing EFlows datasets
Task 4	Mine EFlows data sets for rivers and estuaries
Task 5	Test the generic indicators, links and response curves for SADC rivers
Task 6	Links to co-funded activities
Task 7	Report and disseminate the outcomes

1.3.3 Project team

The project team comprised researchers (Table 1.2), who were individually or severally responsible undertaking the various tasks and internal review of the outcomes, and the members of the project Reference Group (Table 1.3) responsible for additional oversight and quality control.

Table 1.2 Contract #: C2020-00437: Researchers

Researcher	**Affiliation**
Prof. Cate Brown	Southern Waters
Prof. Lara van Niekerk	CSIR
Dr Heidi van Deventer	CSIR
Dr Alison Joubert	Southern Waters
Mr Hassan Bukhari	Southern Waters; University of Stellenbosch – PhD candidate
Dr Karl Reinecke	Southern Waters
Prof. Janine Adams	Nelson Mandela University
Dr Lindie Smith-Adoa	CSIR
Dr Christel Hansen	University of Pretoria
Ms Lukho Goso	University of Pretoria – MSc candidate
Prof. Stephen Lamberth	Department of Forestry, Fisheries and Environment
Prof. Susan Taljaard	CSIR
Mr Steven Weerts	CSIR
Dr Daniel Lemley	Nelson Mandela University
Prof. Jackie King	Southern Waters

Table 1.3 Contract #: C2020-00437: Reference Group members

Member	**Affiliation**
Mr Bonani Madikizela – Chairperson	Water Research Commission
Mr Atwaru Yakeen	Department of Water and Sanitation
Mr Vaqar Zakari	Hagler Bailly Pakistan
Prof. Gordon O'Brien	University of Mpumalanga
Dr Lois Koehnken	L Koehnken Pty Ltd
Prof. Dominic Mazvimazi	University of the Western Cape
Ms Jackie Jay	Department of Forestry, Fisheries and the Environment
Dr Patsy Scherman	Southern Waters; Scherman Environmental

1.3.4 Linked post-graduate studies

Two post-graduate studies were linked to the project, *viz*.:

- An MSc dissertation entitled "*Using geospatial methods to assess the biodiversity, threat status, and protection levels of Africa's rivers*" by Ms Lukho Goso; registered at the University of Pretoria (UP). Supervisors: Dr Heidi Van Deventer (CSIR, UP), Dr Christel Hansen (UP), and Dr Lindie Smith-Adao (CSIR).
- A PhD dissertation entitled "*The importance of the Ecosystem-Based Approach in the development of rivers*" by Mr Hassan Bukhari; registered at the University of Stellenbosch (US). Supervisors: Prof. Karen Esler (US), Prof. Cate Brown (Southern Waters) and Dr Alison Joubert (Southern Waters).

1.4 Report outline

This report is the Eco-Social Assessments of Aquatic Ecosystems (Volume 1): Library of Generic Relationships for SADC Rivers and Estuaries. It is one of three products from this project:

- Eco-Social Assessments of Aquatic Ecosystems (Volume 1): Library of Generic Relationships for SADC Rivers and Estuaries
- Eco-Social Assessments of Aquatic Ecosystems (Volume 2): Notes for using Generic Relationships in DRIFT
- A DRIFT database setup using the generic indicators, links and response curves for rivers presented in this report. It is called DRIFT-Generic-SADC.

The report is structured to give prominence to the main outputs of the project which were the development of generic indicators, links and response curves for SADC rivers and estuaries. To this end some of the outputs from the tasks that laid the groundwork, such as the typologies of major SADC rivers and estuaries were moved to the appendices. The appendices also outline the usefulness of information generated in EFlows assessments in global and national reporting processes.

The first two sections of the body of the report are an introduction (this section) and an overview of DRIFT (Section 2). Thereafter, the report is arranged as follows:

Section 3	Generic indicators, links and response curves for SADC rivers
Section 4	Generic indicators, links and response curves for SADC estuaries
Section 5	Review and testing
Section 6	Recommendations for improving on the generic indicators link and response curves, and enhancing the accessibility of ecosystem-based EFlows approaches.
Appendix A	Typology of major SADC rivers and estuaries
Appendix B	A comparative review of decision support tools routinely used by selected transboundary river basin organisations
Appendix C	The use of ecosystem-based EFlows assessment outputs for global and national reporting processes.

2 OVERVIEW OF DRIFT

DRIFT is a model and database of eco-social information and knowledge used to predict potential changes to aquatic ecosystems as a result of potential future water-resource developments. DRIFT has been used to inform assessments for river channels, floodplains, wetlands, lakes and estuaries. It has also recently been applied to assess implications of changes in the flow of river water and sediments for the near-shore marine ecosystem.

2.1 Modules

DRIFT comprises three modules: (1) Setup, (2) Knowledge capture and (3) Analysis (Figure 2.1).

These three modules, with all their components, are presented within the cream block at the bottom of Figure 2.1. The elements that provide input to and outputs from these are indicated in the area above the cream block.

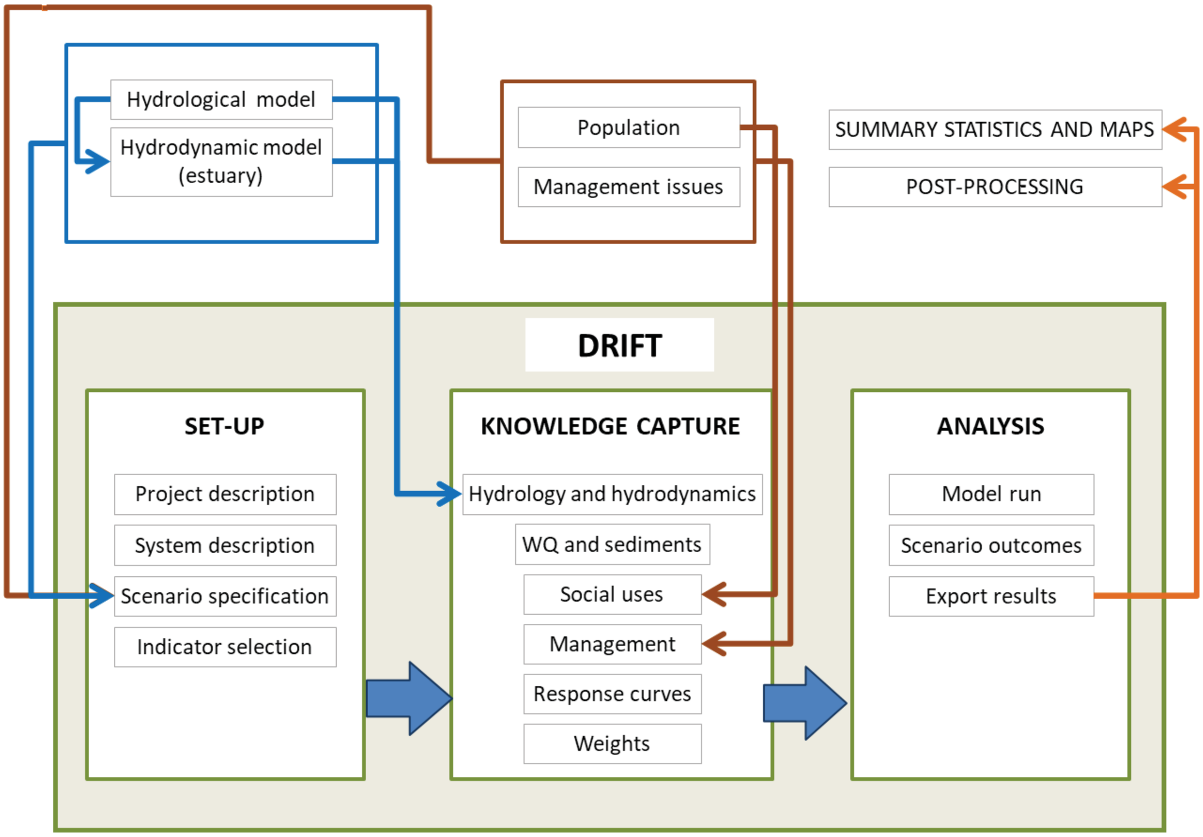


Figure 2.1 **Arrangement of modules in DRIFT (light-brown shading) and inputs/outputs from/to external models/data sources.**

The first two modules deal with the setup, population and calibration of the flow-eco-social relationships that are used to predict the ecosystem's response to potential development/ management actions. The third module is used to generate results once the first two modules have been configured, and to export the output data detailing the predictions for the scenarios under consideration to Microsoft Excel for post-processing and reporting.

2.2 Representative reaches and sites

DRIFT focuses on representative river reaches (EFlows zones) and sites (EFlows sites) that are linked in terms of the movement of water, sediments and biota. The designated EFlows sites in each zone are the focus for all biophysical data collection/collation, hydrological/hydraulic modelling, indicator selection, and reporting. Socio-economic data collection/collation, indicator selection and reporting are done for socio-economic zones that draw information proportionally from more than one EFlows site/zone.

2.3 Disciplines

The number of disciplines in a DRIFT database (DB) depends on the river/estuary, the aims of the assessment and the available budget. Minimum requirements are hydrology and one or more of:

- Hydraulics/hydrodynamics
- Water quality
- Geomorphology
- Riparian vegetation
- Algae
- Macroinvertebrates
- Fish.

The hydrodynamics discipline is particularly important for estuaries, as this is where interaction between river inflows to the estuary and tidal action is modelled, which provides, inter alia, the salinity profiles for an estuary that are central to EFlows assessments in estuaries.

However, DRIFT has been set up for a wide range of disciplines. In addition, to the list above, the DRIFT DBs include, variously:

- Water quality
- Herpetofauna
- Water birds
- Mammals.

Several of the DRIFT DBs also include socio-economic aspects, such as:

- Sediment mining
- Farming (crop farming, livestock grazing)
- Fisheries
- Amenity value and / or other non-material benefits

- Public health risks.

2.4 Hydrobiological flow seasons

DRIFT uses four hydrobiological flow seasons:

- **Dry Season (Dry)**. Flows are much less than the annual average and there is relatively little *natural* flow variability from day to day.
- **Transition Season 1 (T1)**. A time of transition between the end of the Dry Season and the start of the Flood Season. Flows increase but not necessarily rapidly. A number of spates or 'freshets' might typically signify a number of false starts to the Flood Season, with flows receding again after each one.
- **Flood/Wet Season (Flood)**. This is initially characterized by a number of periods of accelerated rates of increasing flow until the annual peak discharge is reached. There may be a number of pulses in this process but overall there is a clear single flood-pulse hydrograph.
- **Transition Season 2 (T2)**. A second transition season between the end of the Flood Season and the start of the Dry Season, during which time the rate of flow recession remains higher than in the Dry Season. In some years there may be late but relatively minor spate events.

2.5 Indicators and links

For a given project, discipline-specific indicators and the links between them are derived by the EFlows team of specialists. Some of these are *external driving indicators* that are generated outside of the DRIFT (Section 2.5.1) and others are *internal eco-social indicators* whose predicted changes are provided through response curves in DRIFT (Section 2.5.2).

2.5.1 External 'driver' indicators

The minimum requirement for DRIFT is daily hydrological time-series data for the baseline situation, and simulations of how these are expected to change with water-resource development, and/or climate change.

Where an external sediment model is available, sediment time series are generated to accompany the hydrology time series and input into DRIFT. For a rapid deployment of DRIFT, where it is unlikely that there is an external sediment model available to route sediments through the basin, sediment is set at 100% for the baseline and then adjusted depending on the water resources being developed, e.g. if sediment is trapped by a dam. In this case, the sediment indicators at each site are linked with upstream sites.

In some cases, depending on study requirements, external hydraulic and hydrodynamic models may be used to provide hydraulic timeseries data; and external water quality models used to provide water quality timeseries data.

All the time series must use the same period, which should be at least 30 years, e.g. 1954-2023.

DRIFT is set-up with reference scenarios. The reference scenarios are:

- Baseline
- Naturalised.

Thereafter, simulated time series over the same period are produced for the scenarios to be analysed.

Once imported into DRIFT, the time series are summarised into ‘driver’ indicators reported as annual values or as values for one or more of four hydrobiological flow seasons (Section 2.4):

- Dry Season (Dry).
- Transition Season 1 (T1)
- Flood/Wet Season (Flood)
- Transition Season 2 (T2).

A fairly typical example (from the DRIFT – Lower Kafue Sub-Catchment database (DRIFT-LKSC)) of the set of modelled indicators and the seasons for which they are calculated is provided in Table 2.1.

Table 2.1 DRIFT external ‘driver’ indicators typically used for rivers and estuaries (example from the DRIFT-LKSC database).

Discipline		**Indicator**	**Units**
Hydrology	Annual	Mean annual runoff	m^3/s
	Dry Season	Onset	calendar week
		Duration	days
		Minimum 5-day discharge	m^3/s
		Average daily volume	$m^3 \times 10^6$
	Transition Season 1	Average daily volume	$m^3 \times 10^6$
	Flood/Wet Season	Onset	calendar week
		Duration	days
		Maximum 5-day discharge	m^3/s
		Average daily volume	$m^3 \times 10^6$
		Flood volume	$m^3 \times 10^6$
	Transition Season 2	Average daily volume	$m^3 \times 10^6$
Floodplain hydrodynamics (for all seasons above)		Onset of inundation/drying	calendar week
		Duration of inundation for various depth ranges	days
		Inundated area (total and various depth ranges)	km^2
		Average velocity	m/s
		Maximum velocity	m/s
		Minimum velocity	m/s
		Average depth	m
		Maximum depth	m
		Minimum depth	m
Sediments (for all seasons above)		Sediment concentration/load	% of Baseline
Water quality (estimated annual)		Phosphorous	% of Baseline

2.5.2 *Internal eco-social indicators*

Eco-social indicators are a set of indicators that reflect important aspects of the riverine ecosystem, resources used by human that are reliant on the ecosystem and human pressures on those resources (Table 2.2). They are deemed to be sensitive to a change in the driver indicators in Table 2.1 by changing in one of the following ways:

- abundance/size, e.g. fish
- extent (area), e.g. cover of riparian tree community on upper dry bank
- concentration, e.g. sediments and nutrients.

Indicators are selected within each discipline, with due consideration of their relevance for other disciplines. For instance, the geomorphological indicator 'Exposed sandy habitat in the dry season' can be selected because it represents a prominent channel attribute as well as an important habitat for birds (e.g. African Skimmer).

Table 2.2 DRIFT-LKSC eco-social indicators (Southern Waters 2021)

Discipline	Indicator	Discipline	Indicator
Geomorphology	Sediment	Fish	Small rheophilic species
	Channel incision		Limnophilic species
	Levee erosion		Floodplain dependent species
	Floodplain deposition		Eurytopic (generalist) species
	Channel bank deposition		Cichlid species (breams)
	Inundated sandy habitat in the dry season		Non-native species
	Exposed sandy habitat in the dry season	Invertebrates	Red claw crayfish
	Exposed rocky habitat in the dry season	Birds	Wattled crane
	Bed material grain size		Goliath heron
Water quality	Phosphorus		African skimmer
Vegetation	Floating aquatics – exotic (water hyacinth)		Openbill stork
	Reeds and grasses		White-faced duck
	Riparian trees and shrubs		African fish eagle
	Rooted aquatics		African pied wagtail
	Mimosa	Large mammals	Kafue lechwe
	Papyrus and bulrushes		Hippopotamus
	Wet grasses	Resource management	Fire damage
	Dry grasses		Fishing gear
	Terrestrial trees and shrubs		Fishing season/location restrictions
			Stocking rate (of livestock)
			Access
			Cultivation in the floodplain
			Control of hyacinth and mimosa
			Harvesting of natural vegetation

The value of an indicator may change with scenarios, and in doing so, drive other indicators to change. For instance, responders to one driver (e.g. exposed sandy habitat disappearing as sediment loads decrease) can become drivers themselves (e.g. change in sandy habitat affects some bird species), thus driving further change (e.g. loss of fish-eating birds affects fish). The simplified linkages between disciplines are shown in Figure 2.2 thus mask the suite of driver-response links used in the analyses. Each line in Figure 2.2 represents a response curve drawn by the specialists and housed in the DRIFT, along with a motivation for its shape. For instance, in DRIFT-LKSC, at EF Site 1, there are 45 indicators across seven disciplines and 272 response curves (Figure 2.2). There are similar numbers of response curves for the other EF sites.

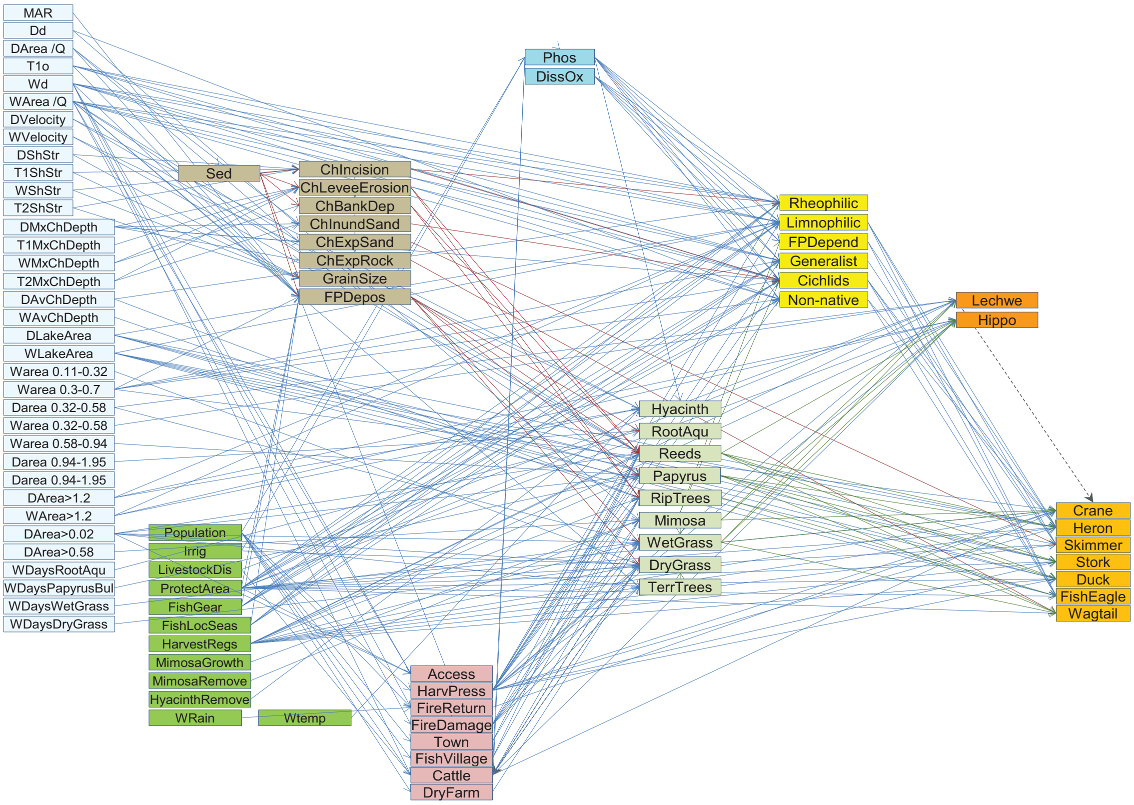


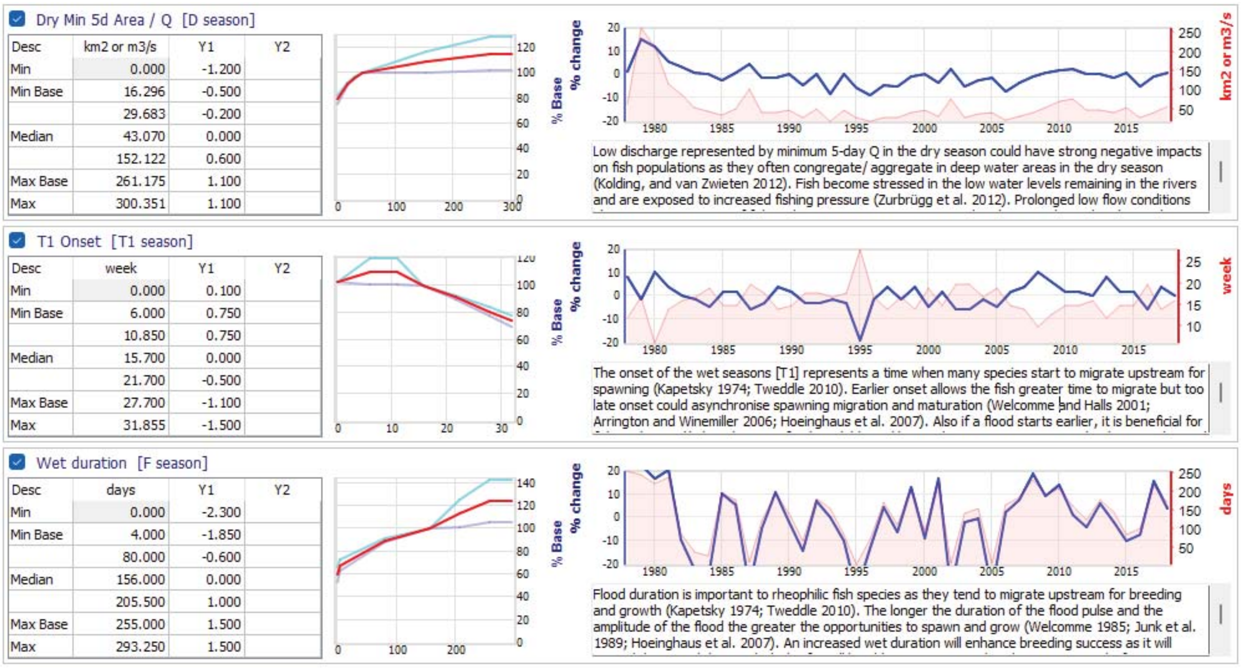
Figure 2.2 **Discipline-level assessment framework for one EFlows Zone in DRIFT-LKSC presented as an example framework. Each line is represented by a response curve.**

The DRIFT database thus forms a knowledge base set up by the EFlows specialists using existing knowledge and understanding about the functioning of the aquatic ecosystems. In this study the database was interrogated to analyse a suite of EFlows scenarios, but it is also available to test other scenarios as part of future studies or planning initiatives.

2.6 Response curves

Response curves are housed in DRIFT and depict the relationship between an eco-social indicator and a driving indicator (e.g. dry season discharge), which can be either externally generated (Section 2.5.1) or another eco-social indicator.

Response curves for the relationship between fish abundance (e.g. *Small rheophilic species,* Table 2.1) and each of dry season min 5-day discharge, onset of transition season 1, and duration of the wet season are shown in Figure 2.3.



☑ Dry Min 5d Area / Q [D season]

Desc	km2 or m3/s	Y1	Y2
Min	0.000	-1.200	
Min Base	16.296	-0.500	
	29.683	-0.200	
Median	43.070	0.000	
	152.122	0.600	
Max Base	261.175	1.100	
Max	300.351	1.100	

Low discharge represented by minimum 5-day Q in the dry season could have strong negative impacts on fish populations as they often congregate/ aggregate in deep water areas in the dry season (Kolding, and van Zwieten 2012). Fish become stressed in the low water levels remaining in the rivers and are exposed to increased fishing pressure (Zurbrügg et al. 2012). Prolonged low flow conditions

☑ T1 Onset [T1 season]

Desc	week	Y1	Y2
Min	0.000	0.100	
Min Base	6.000	0.750	
	10.850	0.750	
Median	15.700	0.000	
	21.700	-0.500	
Max Base	27.700	-1.100	
Max	31.855	-1.500	

The onset of the wet seasons [T1] represents a time when many species start to migrate upstream for spawning (Kapetsky 1974; Tweddle 2010). Earlier onset allows the fish greater time to migrate but too late onset could asynchronise spawning migration and maturation (Welcomme and Halls 2001; Arrington and Winemiller 2006; Hoeinghaus et al. 2007). Also if a flood starts earlier, it is beneficial for

☑ Wet duration [F season]

Desc	days	Y1	Y2
Min	0.000	-2.300	
Min Base	4.000	-1.850	
	80.000	-0.600	
Median	156.000	0.000	
	205.500	1.000	
Max Base	255.000	1.500	
Max	293.250	1.500	

Flood duration is important to rheophilic fish species as they tend to migrate upstream for breeding and growth (Kapetsky 1974; Tweddle 2010). The longer the duration of the flood pulse and the amplitude of the flood the greater the opportunities to spawn and grow (Welcomme 1985; Junk et al. 1989; Hoeinghaus et al. 2007). An increased wet duration will enhance breeding success as it will

Figure 2.3 **A snapshot from the DRIFT-LKSC database showing three of 11 response curves and explanations for *Small rheophilic species* at EF Site 6**

In Figure 2.3, the red line in the first set of graphs is the mean response, and the light blue and darker blue lines represent the uncertainty (upper and lower limits). In the second set of graphs (time series), the solid pink series show the annual values for the linked indicator, e.g. wet season duration, in the baseline dataset. The blue line in these time series graphs shows the annual response of *Small rheophilic species* to the baseline variations in the linked indicator only, i.e. excluding any other responses. These variations are around a mean baseline value of 100% for the indicator, *Small rheophilic species*.

The units on the x-axis depend on the driving indicator under consideration. For instance, for the onset of the transition season 1 (T1 onset; Figure 2.3), these are in calendar weeks.

The y-axis may refer to abundance as in Figure 2.3, but also to other measures such as concentration or area, depending on the indicator. Response curves were constructed using severity ratings (Table 2.3).

Table 2.3 **DRIFT severity ratings and their associated gains and losses – a negative score means a loss in abundance relative to baseline, a positive means a gain**

Severity rating	Severity	% abundance change
5	Critically severe	501% gain to ∞ up to pest proportions
4	Severe	251-500% gain
3	Moderate	68-250% gain
2	Low	26-67% gain
1	Negligible	1-25% gain
0	None	no change
-1	Negligible	80-100% retained
-2	Low	60-79% retained
-3	Moderate	40-59% retained
-4	Severe	20-39% retained
-5	Critically severe	0-19% retained includes local extinction

Each response curve is accompanied by an explanation of its importance and literature references to support the relationship it depicts. For the example in Figure 2.3, the explanation for the *Small rheophilic species* response curve for wet season duration reads as follows:

> "*Flood duration is important to rheophilic fish species as they tend to migrate upstream for breeding and growth (Kapetsky 1974; Tweddle 2010). The longer the duration of the flood pulse and the amplitude of the flood the greater the opportunities to spawn and grow (Welcomme 1985; Junk et al. 1989; Hoeinghaus et al. 2007). An increased wet duration will enhance breeding success as it will extend the period during which the fry will be able to stay in peripheral nursery areas before returning to the main channels and become vulnerable to predation (Merron and Bruton 1988; Winemiller and Kelso-Winemiller 2003; Peel 2012; Bell-Cross 1974).*"

The response curves do not address any of the scenarios directly. The curves are drawn for a range of possible changes in each linked indicator. The ranges may extend beyond changes expected in any of the scenarios. The curves and their explanations, therefore, may include conditions that may not occur under any of the scenarios, but are needed for complete and robust response curves. In addition, each response curve assumes that all other conditions are at Baseline.

The response curves are used to evaluate scenarios by taking the values of each flow or other driver indicator for a scenario, and reading, from the response curve, the responding values of the eco-social indicator. For each season of the hydrological record, and for each eco-social indicator, these responding values (severity ratings) corresponding to the value of a driving indicator is read off its response curve and converted to a percentage change. The percentage changes in response to each driving indicator are combined to produce an overall change for each season. This provides an indication of how abundance, area or concentration of an indicator is expected to change over time under the scenario's conditions, relative to the changes that would have been expected under baseline conditions.

2.7 Generic indicators, links and response curves

The study evaluated driver-response relationships in 11 DRIFT databases developed for 64 sites/ zones across several river basins in southern Africa. The datasets contained indicators and response curves for river, floodplain, and wetland ecosystems and captured the links between hydrology, hydraulics, sediment, geomorphology, riparian vegetation, macroinvertebrates, fish and social use.

The analysis of the DRIFT databases for river sites in SADC was presented in Progress Report #4. The main outcomes of this analysis were:

- SADC river types did not seem to influence the selection of indicators
- Habitat availability at a site played the main role in the indicators that were selected
- For individual indicators, the driver-response relationships were mostly convergent for geomorphology, vegetation, macroinvertebrates, and fish.
- Severity ratings for the linked indicators tested were statistically equal for all sites in each database.
- Hydraulics/hydrodynamics links, particularly those for floodplains and wetlands, present a challenge for standardisation as typically these are derived from hydrodynamic modelling of the focus areas.

The findings supported the development of generic ecosystem indicators, links and response curves for river and EFlows assessments. The review is being written up as a journal paper:

> BUKHARI H, BROWN C, ESLER K and JOUBERT A (In prep.) A framework for rapid holistic ecosystem based modelling of rivers in southern Africa.

2.8 Major assumptions and limitations

Predicting the effect of changes in flow, sediment, connectivity, and human pressures on rivers is difficult because the actual trajectory and magnitude of the change is dependent on so many other variables, such as climate, politics, road networks, economics, and regulations. Thus, several assumptions and limitations apply to the generic library of DRIFT indicators and response curves:

- This library was compiled based on the reasoning as described by discipline experts for a large number of sites across the eleven DRIFT models. Subsequently, the underlying uncertainties, limitations, and assumptions of these constituent DRIFT databases apply to this generic library. In some regards this uncertainty is reduced as multiple databases were used to mostly confirm and rationalise the relationships contained within them.

- For each DRIFT project, the response curves were generated based on the baseline time series of flow and other drivers of ecosystem condition, which should approximate the conditions in the river over the period of record. Should this not be the case, then the baseline for the scenarios would be different to that used and so the scenario predictions, which are relative to this baseline, could also change.
- Capturing the complexity of the system is confounded by the paucity of data. This is a universal problem as, by their nature, human interactions with ecosystems are complex; certainty of the present and possible future characteristics of the ecosystems is not realistic. Instead, it is essential to proceed cautiously, and aid decision-making using the best available information. The alternative is that development and management decisions are made without consideration of the consequences for the supporting ecosystems, eventually making management of sustainability impossible. Data paucity is addressed by this generic library of indicators and response curves by bringing them, the associated explanations and supporting literature into the public domain for transparency and to generate avenues for improvement. They can be updated as new information becomes available and new insights are gained.

As is the case with all ecosystem modelling, the inherent uncertainties mean that attention should be directed toward trends in the sequence of scenarios and the position of scenarios relative to each other, rather than towards absolute values.

3 GENERIC INDICATORS, LINKS AND RESPONSE CURVES FOR SADC RIVERS

3.1 Introduction

The generic indicators, links and response curves presented in this section were derived from a comparative analysis of DRIFT databases for river sites in SADC. Eleven DRIFT databases compiled between 2015 and 2022 were selected for analysis. These comprised 64 sites located on rivers with and without floodplains, wetlands, lakes and deltas (Table 3.1). Most of the basins are located within SADC (Figure 3.1): the Zambezi basin (13 sites; including two on the Zambezi River, six on the Kafue River, and five on the Shire River), the Cubango-Okavango basin (eight sites), the Cunene river (three sites), the Cuanza basin (five sites), the Hlotse basin (five sites), the Usutu-Mhlathuze Water Management Area (eight sites: Mhlathuze – two, Mfolozi – three, Mkuze – one, Upper Pongola – one, Upper Usutu – one), the Pongola Floodplain (12 sites) and Lake Sibaya (one site). One basin, the Kouilou-Niari River Basin (nine sites), is in the Republic of Congo (outside of SADC), but was included because the Kouilou-Niari River is similar in character to many rivers along the west coast of Southern Africa. Four of the database were compiled for EFlows assessments for specific water-resource developments (Batoka Gorge Hydropower Project (HPP) on the Zambezi; Sounda HPP on the Kouilou-Niari; Lesotho Lowlands Water Development Project Phase II on the Hlotse River as part of the Orange-Senqu system; and Baynes Gorge HPP on the Cunene), one was part of a Cumulative Impact Assessment (on the Cuanza: CIA, IFC 2013), three were part of basin planning studies (the Lower Kafue, the Shire River and Elephant Marshes, and the Cubango-Okavango basin), and three were Reserve determinations in terms of the South African Water Act (for the Usutu-Mhlathuze Water Management Area, the Pongola Floodplain and Lake Sibaya; DWAF 2018).

Table 3.1 DRIFT databases included in the assessment

No	River / Basin	Purpose	Client	~Date	# of sites
1	Zambezi	EFlows assessment for Batoka HPP	ERM for Zambezi River Authority	2019	2
2	Zambezi (Kafue)	EFlows assessment for Lower Kafue River Sub-Catchment (LKSC)	GIZ	2021	6
3	Zambezi (Shire)	Climate resilient livelihoods and sustainable natural resources management (basin planning)	Government of Malawi	2016	5
4	Okavango	Resilient Waters Program: Cubango-Okavango Basin and Programme for Transboundary water management in the Cubango-Okavango River basin	USAID, EU, OKACOM	2020	8
5	Cunene	EFlows assessment for Baynes HPP	ERM for Angolan and Namibian Governments	2022	3
6	Cuanza	CIA for hydropower development	ERM for Odebrecht	2015	5
7	Kouilou-Niari	EFlows assessment for Sounda HPP	IFC/AECOM	2017	9

No	River / Basin	Purpose	Client	~Date	# of sites
8	Orange (Hlotse)	EFlows assessment and water quality modelling for Lesotho Lowlands Water Development Project	Ministry of Water, Lesotho	2022	5
9	Usutu-Mhlathuze Water Management Area (WMA)	Reserve determination in the Usutu-Mhlathuze (Usutu, Mkuze, Umfolozi, Mhlathuze, Pongola rivers) (WMA)	Department of Water and Sanitation, South Africa	2015	8
10	Pongola Floodplain	Reserve determination in the Usutu-Mhlathuze WMA	Department of Water and Sanitation, South Africa	2016	12
11	Lake Sibaya	Reserve determination in the Usutu Mhlathuze WMA	Department of Water and Sanitation, South Africa	2016	1

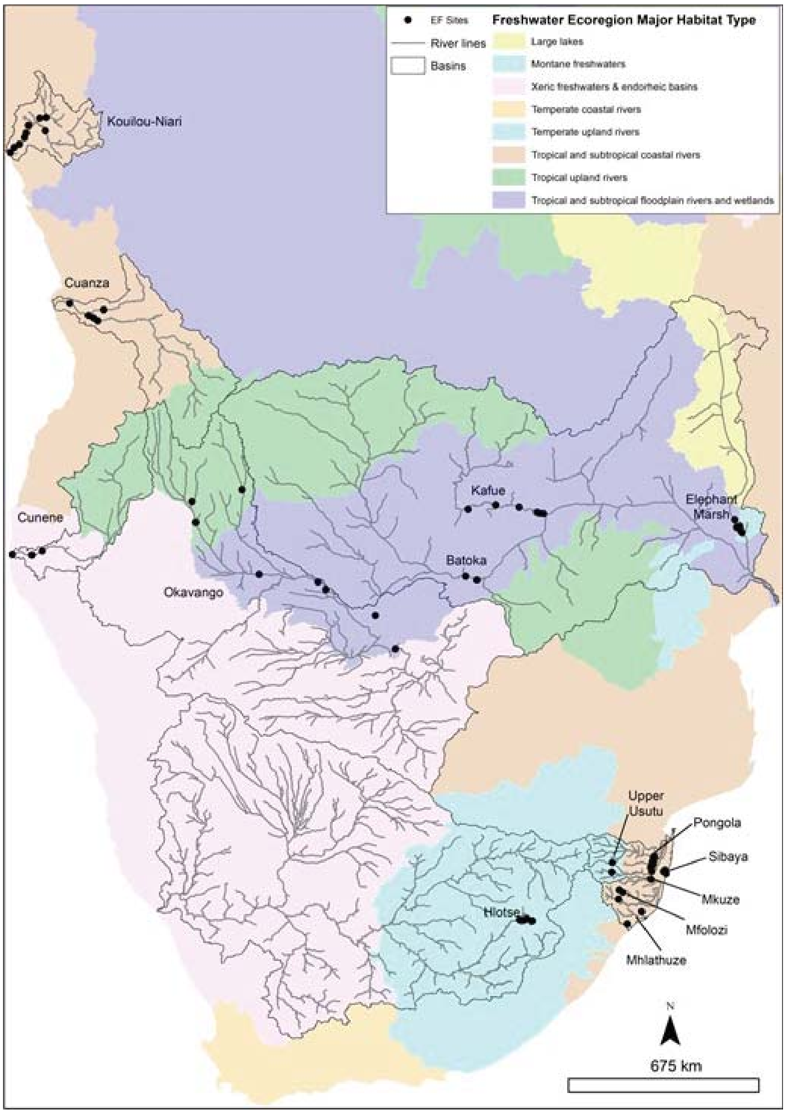


Figure 3.1 The locations of the DRIFT assessment sites

There were a large number of indicators and response curves that had to be compared and rationalised: 70 geomorphology indicators were used across 46 sites and were modelled by 1,447 response-curves; 28 riparian vegetation and algae indicators were used across 64 sites and were modelled by 2,946 response-curves; 54 macroinvertebrate indicators were used across 42 sites and were modelled by 1,255 response-curves; and 84 fish indicators were used across 64 sites and were modelled by 2,536 response-curves.

The generic indicators for SADC river ecosystems are listed in Table 3.2 organised into ecosystem components or "disciplines". The links and relationships for each indicator are described in Sections 3.2 to 3.7. This is a very simplified set of riverine indicators, but they should provide sufficient scope to build a simplified DRIFT EFlows model for most rivers in SADC.

The generic response curves are balanced for the hydrology in DRIFT-Generic_SADC that uses Zambezi River hydrology divided by 100. Re-balancing would be required when the site hydrology is used.

Table 3.2 Generic indicators for SADC river ecosystems

DRIFT Code	Indicator name in DRIFT	Description
Hydrology		
MAR	Mean annual runoff	Average annual runoff (m^3/s)
Do	Dry onset	Onset of the dry season (calendar weeks)
Dd	Dry duration	Duration of the dry season (days)
Dq	Dry min 5-day Q	Minimum of the 5-day running average discharge in the dry season (m^3/s)
Ddv	Dry ave daily vol	Average daily volume in the dry season (Mm^3/day)
T1d	T1 duration	Duration of the T1 season (days)
T1dv	T1 ave daily vol	Average daily volume in the T1 season (Mm^3/day)
Fo	Wet onset	Onset of the flood/wet season (calendar weeks)
Fd	Wet duration	Duration of the flood/wet season (days)
Fq	Wet max 5-day Q	Maximum of the 5-day running average discharge in the wet season (m^3/s)
Fv	Flood volume	Total volume of the flood/wet season (Mm^3)
T2d	T2 duration	Duration of the T2 season (days)
T2dv	T2 ave daily vol	Average daily volume in the T2 season (Mm^3/day)
Geomorphology		
Sed1	Clay and silt	Fine sediments which are often suspended including clay and silt.
Sed2	Sand	Coarse sediments consisting of sand.
Sed3	Gravels and cobble	Bedload sediments including gravels and cobbles
G1	Bed erosion	Erosion processes in the riverbed
G2	Bank erosion	Erosion processes on the riverbanks
G3	Bed sediment size	Mean bed sediment size, an increase reflects a coarsening of the bed sediment size
G4	Embeddedness	Degree of embeddedness
G5	Turbidity	A measure of water clarity
G6	Pool depth	Geomorphic depth of pools in the dry season
G7	Cut banks	Stability of natural cut banks that provide habitat
G8	Riffles	Extent of riffle habitat

DRIFT Code	Indicator name in DRIFT	Description
G9	Islands and bars	Number and extent of stable consolidated islands / vegetated mid-channel bars
G10	Backwaters and secondary channels	Area of backwaters and secondary channels
G11	Exposed sandy habitat in the dry season	Exposed sandy habitat in the active channel in the dry season
G12	Exposed cobble habitat in the dry season	Exposed cobble habitat in the active channel in the dry season
G13	Exposed bedrock habitat in the dry season	Exposed bedrock habitat in the active channel in the dry season
G14	Inundated sandy habitat	Extent of sandy habitat inundated by water
G15	Inundated cobble habitat	Extent of cobble habitat inundated by water
G16	Inundated bedrock habitat	Extent of bedrock habitat inundated by water
Riverine Vegetation		
V1	Aquatic plants on rock	Aquatic plants that grow submerged in water and have their roots on wet rocky habitat.
V2	Aquatic plants in sand	Aquatic plants that grow submerged in water and have their roots in wet sandy habitat.
V3	Emergent graminoids	Emergent graminoids are grass like plants rooted in the water and their culms/blades up out of the water: families Poaceae (grass), Cyperaceae (sedge), Juncaceae (rush), Typhaceae (bulrush).
V4	Wetbank grasses	Wet grasses grow on the Wetbank. They are exposed during the dry season and inundated by median flows in the wet season.
V5	Wetbank shrubs and trees	Wet shrubs/trees grow on the Wetbank, where their roots may be in permanent contact with water at low flow. They are flexible and adapted to bending when inundated during the wet season.
V6	Papyrus	*Cyperus papyrus* is a large sedge that grows in slow/barely flowing water.
V7	Reeds evergreen	*Phragmites mauritianus* is a large reed that grows all year round.
V8	Reeds dry dormant	*Phragmites australis* is a large reed that is dormant in winter.
V9	Water hyacinth	Floating exotics grow on the water's surface with roots hanging into the water.
AV1	Agg: Aquatic veg	General aquatic vegetation habitat. Aggregate indicator: Aquatic plants on Rock, Aquatic plants in Sand
AV2	Agg: Marginal and riparian veg	General marginal vegetation habitat. Aggregate indicator: Emergent graminoids, Emergent papyrus, Wetbank reeds evergreen, Wetbank reeds dry dormant, Wetbank grasses, Wetbank shrubs/trees.
Algae		
A2	Filamentous algae	Filamentous algae are colonial algae, which are unpalatable, and change habitat conditions for invertebrates and fish.
A1	Algal biofilms	In freshwater, Algal biofilm comprise predominantly diatoms and unicellular algae that grow on inundated rocky habitat, which are an important food source for invertebrates and fish.
Macroinvertebrates		
M2	Caenidae	Ephemeroptera: Small square-gill mayflies
M3	Heptageniidae	Ephemeroptera: Flatheaded mayflies
M5	Oligoneuriidae	Ephemeroptera: Brush-leg mayflies
M6	Ceratopogonidae	Diptera: Biting midges
M7	Chironomidae	Diptera: Non-biting midges
M8	Simuliidae	Diptera: Blackflies
M9	Elmidae	Coleoptera: Riffle beetles
M10	Hydropsychidae	Trichoptera: Net-spinning caddisflies

DRIFT Code	Indicator name in DRIFT	Description
AM1	Agg: Invert food for inverts	Invertebrate food for other invertebrates. Aggregate indicator: Chironomidae; Ceratopogonidae, Hydropsychidae.
M12	Coenagrionidae	Odonata: Damselflies
M13	Gomphidae	Odonata: Clubtail dragonflies
M14	Perlidae	Plecoptera: Stoneflies
M15	Freshwater snails	Gastropoda: Various
M16	Atyidae	Decapoda: Freshwater shrimps
M17	Palaemonidae	Decapoda: Freshwater prawns
M18	Agg: EPT food for fish	Ephemeroptera, Plecoptera, Trichoptera (EPT) food for fish. Aggregate indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Hydropsychidae, Perlidae.
M19	Agg: Invert food for fish	General invertebrate food for fish. Aggregate indicator: Baetidae; Heptageniidae; Oligoneuriidae; Leptophlebiidae; Hydropsychidae, Perlidae; Caenidae; Simuliidae; Chironomidae; Ceratopogonidae.
Fish		
F1	Riffle dependent fish (small)	Fish that inhabit cobble or rocky habitat in riffles with swiftly flowing water. They may have adaptations that allow them to cling to stones.
F2	Quiet vegetated water fish	Fish that inhabit quiet vegetated waters in river littorals, and backwaters.
F3	Floodplain dependent fish	Fish that are dependent on access to the floodplain for key portions of their life history.
F4	Migratory fish (large)	Fish that must migrate up or downstream to reach their spawning, breeding and / or nursery areas.
F6	Tolerant fish	Fish that are tolerant of a wide range of conditions and do not have specialised flow, geomorphic, or vegetation requirements.
AF1	Agg: Fish abundance	Aggregate indicator: combines fish indicators to provide an estimate of overall fish abundance/biomass
Social		
S1	Fishing resources	Overall fish abundance/biomass available for fishing
S2	Sand and gravel mining resources	Sand, gravel and cobbles on the riverbed available for extraction
S3	Reed harvesting potential	Reeds available for subsistence use
S4	Aesthetic value	Aesthetic appeal of the riverine ecosystem

3.1.1 Aspects excluded from the library

The indicators, links and relationships for SADC rivers and estuaries developed here exclude some aspects of the riverine ecosystem. Although important, they are not captured in the generic library at this stage tend because they are site specific, multi-causal and extremely complex. These include:

- Macro channel shape: Indicators and links relating to changes in macro-channel form are excluded.
- Catchment sediment supply: Sediment supply indicators are limited to those that capture sediment movement down the river from an upstream site to a downstream site. Indicators and links relating to changes in baseline levels of sediment supply from the surrounding catchment are not included.
- Hydraulic and hydrodynamic indicators. Although hydraulic and hydrodynamic indicators, such as depth, velocity, shear stress, are extremely useful and are often preferred link to aspects of

the flow regime, they are highly site specific and require detailed cross-sectional survey data and modelling. Generation of site- or reach-specific hydraulics is crucial in detailed EFlows assessments, but impossible to include in the library of indicators, links and relationships for SADC rivers and estuaries. Instead, where relevant, the links are made directly to hydrological indicators. Where the relevant hydraulic data are available, these links should be transferred to the appropriate hydraulic indicator.

- Floodplain, lake and wetlands: Indicators and links for floodplains, lakes and wetlands are excluded as these are highly reliant on an understanding of the site-specific hydrodynamics (see point above).
- Invasive species: Some indicators and links are included for invasive species, but these are incomplete and should be used with caution.
- Within day fluctuations in discharge: Large within-day fluctuations in discharge are typically the result of hydro-peaking operation in an upstream hydropower plant, and can be very damaging to river ecosystems. At this stage, however, the generic library excludes the indicators, links and response curves needed to assess these impacts; mainly because they require hourly hydrological data and hydrodynamic modelling.
- Degradation of the river ecosystem due to anthropogenic pressures are not captured because the level of pressures, the current condition of the ecosystem, and the capacity of the ecosystem to withstand social pressures are highly site specific.

3.1.2 Layout

The response curves in this document are formatted to match the layout in the DRIFT software. The first line includes the linked driver and the season (D, T1, F, T2 or All season) in which the response curve will be applied.

The calculations in DRIFT follow a hierarchical order:

- upstream to downstream
- through the disciplines, viz.: hydrology, hydraulics, geomorphology, water quality, riparian vegetation, macroinvertebrates and fish

The default setting is that each link is to a driving indicator at the same site and in the same season. If, however, a responding indicator is linked to a driving indicator located at a downstream site (e.g. for migration) or to a discipline higher up in the hierarchy, it is then linked to previous season or previous year. These special cases are denoted by “Step = -1” in the first line.

The first column of numbers represents the x axis of the response curve, and the second column of numbers provides the severity scores. Severity scores are translated into a percentage change from baseline which is plotted in the response curve (Table 2.3). In the case where the response curves have hydrology driving indicators, the x axis will be populated by DRIFT with physical units such as m^3/s for discharge, Mm^3 for daily volume, days for season duration, etc. These axes will depend on the input baseline hydrology which will vary from site to site. Thus, for the library, the x axes in the generic response curves are placeholders, and would be replaced once the hydrology for a particular site is entered into DRIFT.

3.1.3 Setting-up a generic DRIFT

Setting up a DRIFT DB for a particular reach/site would involve:

- creating a new DRIFT DB
- entering the geographical position of the reach/site
- generating baseline daily time series for hydrology, either measured or simulated, and sediment supply, and importing these into DRIFT
- selecting a sub-set of the generic indicators for each of geomorphology, riparian vegetation, macroinvertebrates and fish based on characteristics of the target reach/site
- entering the selected indicators, links and curves into the DRIFT database
- adjusting of RCs, if needed
- generating scenario daily time series for hydrology and sediment supply, and importing these into DRIFT
- analysing and exporting the results.

Setting up DRIFT for a basin would involve the same steps as outlined above, but for numerous sites in the basin, and setting up connections between sites.

3.2 Hydrology

At a minimum DRIFT requires a hydrology time series and once imported into DRIFT, the time series are summarized into 'driver' indicators reported as annual values or as values for one or more of four hydrobiological flow seasons (Section 2.4):

- Dry Season (Dry).
- Transition Season 1 (T1)
- Flood/Wet Season (Flood)
- Transition Season 2 (T2).

The generic library uses a limited set of eleven hydrology indicators (listed in Table 3.2) although additional ones can be defined (e.g. those that describe within day variations due to hydropeaking). Other external time series such as those for sediment can also be used however, where possible these disciplines are defined within DRIFT as ecosystem indicators to limit external data requirements.

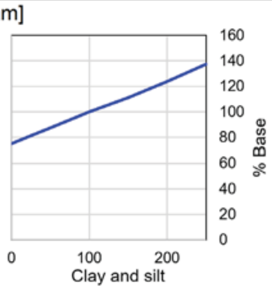
3.3 Geomorphology

3.3.1 Clay and silt

The load of fine sediments (clay and silt) transported from upstream relative to the baseline (Table 3.3):

Purpose:	Fine sediments can affect organisms directly by impairing vision and clogging gills, and indirectly by smothering habitats. Fine sediments also determine turbidity which controls light penetration and hence vegetation extent and growth.
Grain size:	<0.0625 mm (Wentworth 1926)
Links:	Clay and silt (upstream site).

Table 3.3 Clay and silt links, explanations and supporting literature

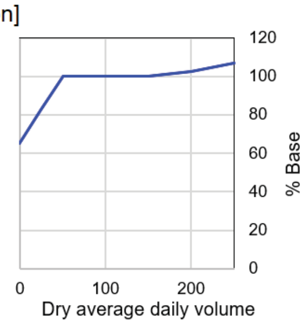
<table>
<tr><th colspan="2">CLAY AND SILT</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>Clay and silt [All seasons, Site=upstream]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Clay and silt (UPSTREAM): Clay and silt is carried downstream by the river (Vercruysse et al. 2017). Without further information it is assumed that the sediment at this site has a 1:1 relationship with the upstream site.</td></tr>
<tr><td colspan="2">VERCRUYSSE K, GRABOWSKI RC and RICKSON RJ (2017) Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. Earth-Science Reviews 166 38-52.</td></tr>
</table>

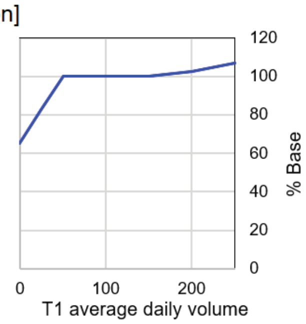
3.3.2 Sand

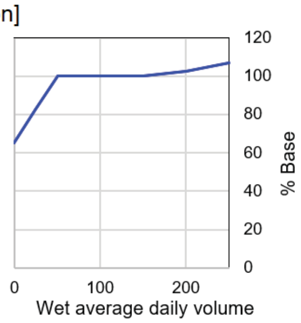
The amount of sand transported from upstream relative to the baseline (Table 3.4). The sand indicator includes fine to coarse sand:

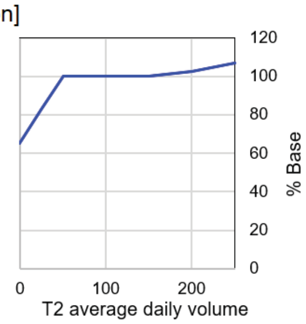
Purpose:	Sediment supply and water flow are the main drivers of erosion and deposition in river systems. Sandy habitats are exploited by fish and other aquatic organisms for spawning and nesting. Sand in suspension can also increase the abrasive effect of water flows.
Grain size:	0.0625 to 2.0 mm (Wentworth 1926)
Links:	Dry average daily volume; T1 average daily volume; Wet average daily volume; T2 average daily volume; Sand (upstream site).

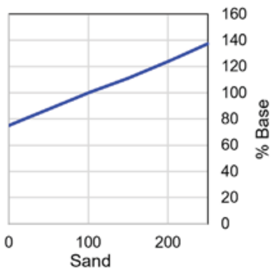
Table 3.4 Sand links, explanations and supporting literature

<table>
<tr><th colspan="2">SAND</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>Dry average daily volume [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.1</td></tr>
<tr><td>Max</td><td>250</td><td>0.4</td></tr>
</table>

</td><td>Dry average daily volume: Sediment transport requires moving water, as the water flow creates small upward currents (turbulence) that keep the particles above the bed (Southard 2006). In general, the greater the flow, the more sediment that will be conveyed (Hickin 1995).</td></tr>
</table>

<table>
<tr><td colspan="2">**SAND**</td></tr>
<tr><td>**Link and response curve**</td><td>**Explanation and supporting literature**</td></tr>
<tr><td>
<table>
<tr><td colspan="3">T1 average daily volume [T1 season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.1</td></tr>
<tr><td>Max</td><td>250</td><td>0.4</td></tr>
</table>


</td><td>T1 average daily volume: Sediment transport requires moving water, as the water flow creates small upward currents (turbulence) that keep the particles above the bed (Southard 2006). In general, the greater the flow, the more sediment that will be conveyed (Hickin 1995).</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Wet average daily volume [F season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.1</td></tr>
<tr><td>Max</td><td>250</td><td>0.4</td></tr>
</table>


</td><td>Wet average daily volume: Sediment transport requires moving water, as the water flow creates small upward currents (turbulence) that keep the particles above the bed (Southard 2006). In general, the greater the flow, the more sediment that will be conveyed (Hickin 1995).</td></tr>
<tr><td>
<table>
<tr><td colspan="3">T2 average daily volume [T2 season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.1</td></tr>
<tr><td>Max</td><td>250</td><td>0.4</td></tr>
</table>


</td><td>T2 average daily volume: Sediment transport requires moving water, as the water flow creates small upward currents (turbulence) that keep the particles above the bed (Southard 2006). In general, the greater the flow, the more sediment that will be conveyed (Hickin 1995).</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Sand [All seasons, Site=upstream]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Sand (UPSTREAM): Sediment is carried downstream by the river (Vercruysse *et al.* 2017). Without further information it is assumed that the sediment at this site has a 1:1 relationship with the upstream site.</td></tr>
<tr><td colspan="2">HICKIN EJ, eds. (1995) *River Geomorphology*. Wiley Press, Chichester.
SOUTHARD J (2006) 12.090 Introduction to Fluid Motions, Sediment Transport, and Current-Generated Sedimentary Structures, Course Textbook. In MIT Open Courseware: Massachusetts Institute of Technology.
VERCRUYSSE K, GRABOWSKI RC and RICKSON RJ (2017) Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. *Earth-Science Reviews* **166** 38-52.</td></tr>
</table>

3.3.3 Gravel and cobbles

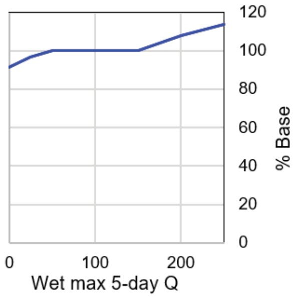
The load of gravels and cobbles transported from upstream relative to the baseline (Table 3.5). The gravel and cobble indicator includes granules, gravels, small pebbles and cobbles:

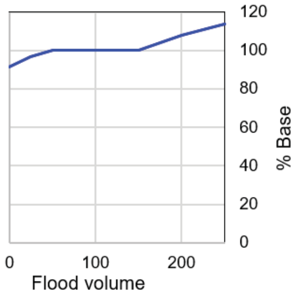
Purpose: Sediment supply and water flow are the main drivers of erosion and deposition in river systems. Gravels and cobbles generally only move during high flows and are stable during low and medium flows.

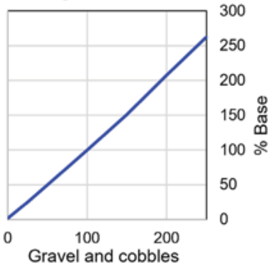
Grain size: 2 to 256 mm (Wentworth 1926)

Links: Wet max 5-day Q; Flood volume; Gravels and cobbles (upstream site).

Table 3.5 Gravel and cobbles links, explanations and supporting literature

<table>
<tr><th>GRAVEL AND COBBLES</th><th></th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Wet max 5-day Q: Gravel and cobbles can be transported only at very high velocities, approximated by the peak discharge in the wet season (Hickin 1995).</td></tr>
<tr><td>
Flood volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Flood volume: Flood volume in addition to the peak discharge supports the movement of cobbles downstream (Eaton <i>et al.</i> 2001).</td></tr>
<tr><td>
Gravel and cobbles [F season, Site=upstream]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-5.7</td></tr>
<tr><td>Min Base</td><td>25</td><td>-4.3</td></tr>
<tr><td></td><td>50</td><td>-2.9</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>2.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.8</td></tr>
<tr><td>Max</td><td>250</td><td>3.1</td></tr>
</table>


</td><td>Cobbles and Boulders (UPSTREAM): Bedload sediment is carried downstream by the river (Vercruysse <i>et al.</i> 2017). Without further information it is assumed that the sediment at this site has a 1:1 relationship with the upstream site.</td></tr>
<tr><td colspan="2">HICKIN EJ, eds. (1995) <i>River Geomorphology</i>. Wiley Press, Chichester.
EATON BC and LAPOINTE MF (2001) Effects of large floods on sediment transport and reach morphology in the cobble-bed Sainte Marguerite River. <i>Geomorphology</i> 40 (3-4) 291-309.
VERCRUYSSE K, GRABOWSKI RC and RICKSON RJ (2017) Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. Earth-Science Reviews 166 38-52.</td></tr>
</table>

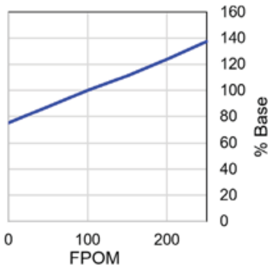
3.3.4 FPOM

FPOM or Fine Particulate Organic Matter is composed of small fragments of detritus and aggregates of dissolved organic matter (Table 3.6):

Purpose: FPOM is an important component of many ecosystem processes as it represents a major pathway of organic matter transport and export and is thus an important consideration in ecosystem organic matter budgets. It also functions as an important food resource for many filter-feeding invertebrates as well as for some vertebrates.

Links: FPOM (upstream site).

Table 3.6 FPOM links, explanations and supporting literature

<table>
<tr><th>FPOM</th><th></th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">FPOM [All seasons, Site=upstream]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>FPOM (UPSTREAM): FPOM is carried downstream by the river (Vercruysse *et al.* 2017). Without further information it is assumed that the FPOM at this site has a 1:1 relationship with the upstream site.</td></tr>
<tr><td colspan="2">VERCRUYSSE K, GRABOWSKI RC and RICKSON RJ (2017) Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. Earth-Science Reviews **166** 38-52.</td></tr>
</table>

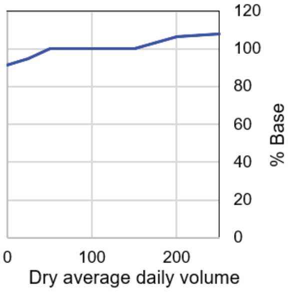
3.3.5 Bed erosion

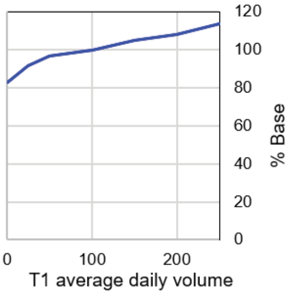
Bed erosion reflects erosion processes in the channel bed such as channel incision. It is a combination of river energy, sediment supply and timing of sediment delivery (Table 3.7):

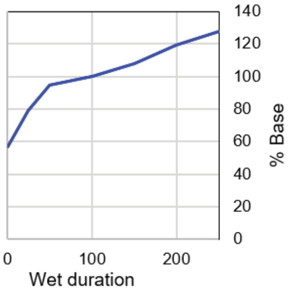
Purpose: Erosion and deposition are the driving process in the composition of the riverbed and hence the creation of aquatic habitats.

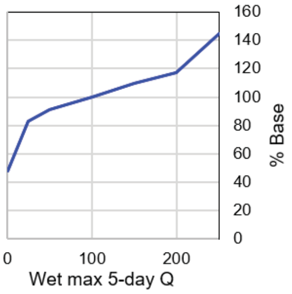
Links: Dry average daily volume; T1 average daily volume; Wet duration; Wet max 5-day Q; T2 average daily volume; Sand.

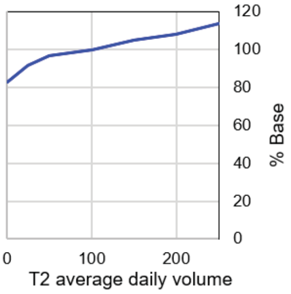
Table 3.7 Bed erosion links, explanations and supporting literature

<table>
<tr><th colspan="2">BED EROSION</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Dry average daily volume [D season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.3</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.3</td></tr>
<tr><td>Max</td><td>250</td><td>0.5</td></tr>
</table>


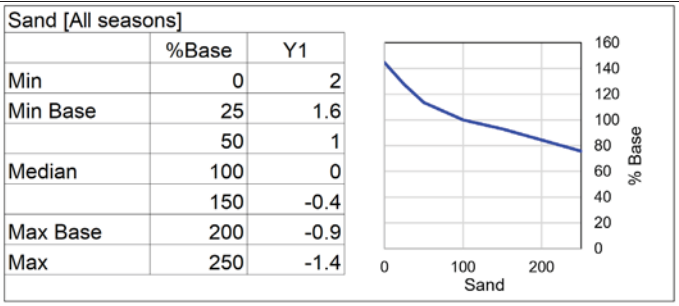
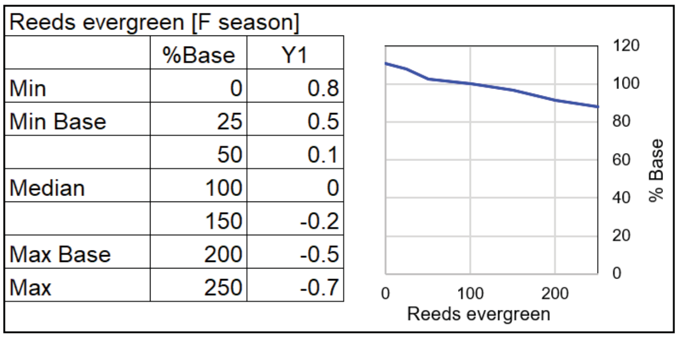
</td><td>Dry average daily volume: The higher the average daily volume during the Dry season the greater the potential for erosion. Dry season flows can winnow fines from the bed.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">T1 average daily volume [T1 season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>T1 average daily volume: The higher the average daily volume during the T1 season the greater the potential for erosion.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet duration [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.2</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.3</td></tr>
<tr><td>Max</td><td>250</td><td>1.6</td></tr>
</table>


</td><td>Wet duration: The longer the duration of the wet season, the greater the potential for erosion. Sediment transport tends to be highest in the early part of the wet season, so the potential for subsequent deposition following erosion decreases as the length of the wet season increases. (Hudson 2003)</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet max 5-day Q [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.7</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.2</td></tr>
<tr><td>Max</td><td>250</td><td>2</td></tr>
</table>


</td><td>Wet max 5-day Q: The higher the peak flows, the higher the shear stress and the greater the potential for erosion (Grove <i>et al.</i> 2013).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">T2 average daily volume [T2 season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>T2 average daily volume: The higher the average daily volume during the T2 season the greater the potential for erosion.</td></tr>
</table>

<table>
<tr><th colspan="2">BED EROSION</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
Sand [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1.6</td></tr>
<tr><td></td><td>50</td><td>1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.9</td></tr>
<tr><td>Max</td><td>250</td><td>-1.4</td></tr>
</table>
</td><td>Sand: The more sediment that is being transported the greater the likelihood that sediment can be 'replaced' through deposition. Sediment supply will have an inverse relationship with erosion.</td></tr>
<tr><td>
Reeds evergreen [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.8</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-0.7</td></tr>
</table>
</td><td>Reeds evergreen (if present in the channel): One hydraulic impact of vegetation in the channel is an increase in flow resistance, physical protection of the alluvial bank and a reduction in conveyance capacity. The aboveground portion of biomass helps increase sedimentation both by reducing the local flow velocities and by providing additional horizontal surface per volume upon which sedimentation can occur (Rominger <i>et al.</i> 2010).</td></tr>
<tr><td colspan="2">GROVE R, CROKE J and THOMPSON C (2013) Quantifying different riverbank erosion processes during an extreme flood event. <i>Earth Surface Processes and Landforms</i> 38 (12) 1393-1406.
HUDSON PF (2003) Event sequence and sediment exhaustion in the lower Panuco Basin, Mexico. <i>Catena</i> 52 (1) 57-76.
ROMINGER JT, LIGHTBODY AF and NEPF HM (2010) Effects of Added Vegetation on Sand Bar Stability and Stream Hydrodynamics. Journal of Hydraulic Engineering 136 (12) 994-1002.</td></tr>
</table>

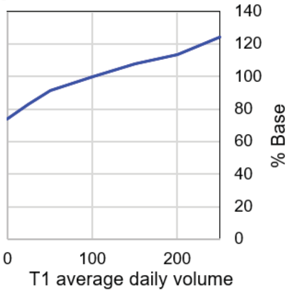
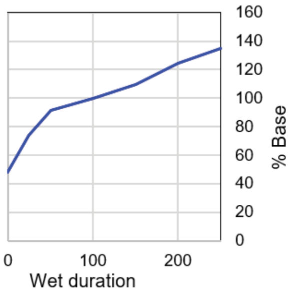
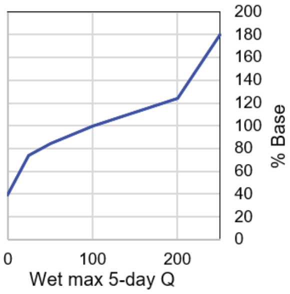
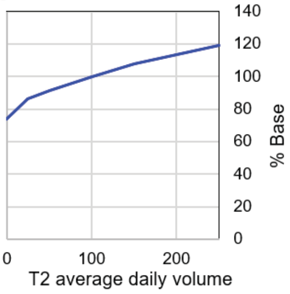
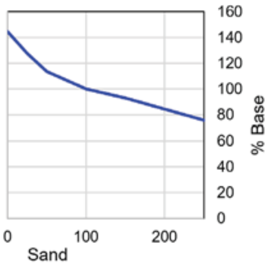
3.3.6 Bank erosion

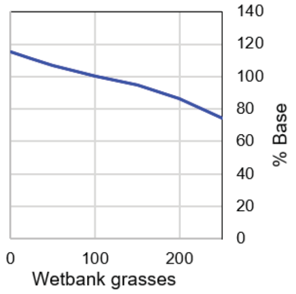
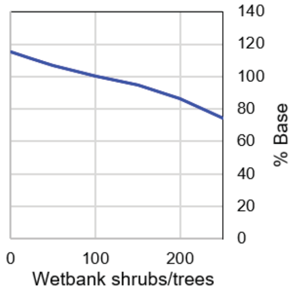
Bank erosion reflects erosion processes on the channel bank. It is a combination of river energy, sediment supply, vegetation and timing of sediment delivery (Table 3.8):

Purpose: Bank erosion cuts into the habitat used by the marginal vegetation communities.

Links: T1 average daily volume; Wet duration; Wet max 5-day Q; T2 average daily volume; Sand; Wetbank grasses; Wetbank shrubs/trees.

Table 3.8 Bank erosion links, explanations and supporting literature

<table>
<tr><th colspan="2">BANK EROSION</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>T1 average daily volume [T1 season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td>
<td>T1 average daily volume: The higher the average daily volume during T1 the greater the potential for erosion. Sensitivity is higher than bed erosion due to the finer sediment in the riverbanks than in the riverbed.</td></tr>
<tr><td>Wet duration [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.5</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.7</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.5</td></tr>
<tr><td>Max</td><td>250</td><td>1.8</td></tr>
</table>

</td>
<td>Wet duration: The longer the duration of the wet season, the greater the potential for erosion. Sediment transport tends to be highest in the early part of the wet season, so the potential for subsequent deposition following erosion decreases as the length of the wet season increases. (Hooke 1979) Sensitivity is higher than bed erosion due to the finer sediment in the riverbanks than in the riverbed.</td></tr>
<tr><td>Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.5</td></tr>
<tr><td></td><td>50</td><td>-0.9</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.9</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.5</td></tr>
<tr><td>Max</td><td>250</td><td>2.5</td></tr>
</table>

</td>
<td>Wet max 5-day Q: The higher the peak flows, the higher the shear stress and the greater the potential for erosion (Grove *et al.* 2013). Sensitivity is higher than bed erosion due to the finer sediment in the riverbanks than in the riverbed.</td></tr>
<tr><td>T2 average daily volume [T2 season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.8</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.3</td></tr>
</table>

</td>
<td>T2 average daily volume: The higher the average daily volume during T2 the greater the potential for erosion. Sensitivity is higher than bed erosion due to the finer sediment in the riverbanks than in the riverbed.</td></tr>
<tr><td>Sand [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1.6</td></tr>
<tr><td></td><td>50</td><td>1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.9</td></tr>
<tr><td>Max</td><td>250</td><td>-1.4</td></tr>
</table>

</td>
<td>Sand: Higher sediment loads increase overbank deposition which counters erosion, while lower sediment loads increase bank erosion (Nicholas and Walling 1996).</td></tr>
</table>

<table>
<tr><th colspan="2">BANK EROSION</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>Wetbank grasses [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.8</td></tr>
<tr><td></td><td>50</td><td>0.4</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.8</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>

</td>
<td>Wetbank grasses: A good grass cover will protect the bank from erosion and promote deposition. Loss of cover exposes the underlying bank making it more susceptible to erosion.</td></tr>
<tr><td>Wetbank shrubs/trees [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.8</td></tr>
<tr><td></td><td>50</td><td>0.4</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.8</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>

</td>
<td>Wetbank shrubs/trees: Riverbank trees and shrubs will stabilise the riverbank and enhance deposition. Both processes will reduce erosion (Rowntree and Dollar 1999; Van Coller <i>et al.</i> 1997).</td></tr>
<tr><td colspan="2">R R GROVE, CROKE J and THOMPSON C (2013) Quantifying different riverbank erosion processes during an extreme flood event. <i>Earth Surface Processes and Landforms</i> 38 (12) 1393-1406.
ROWNTREE KM. and Dollar ES (1999) Vegetation controls on channel stability in the Bell river, eastern cape, South Africa. <i>Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group</i> 24 (2) 127-134.
VAN COLLER ALAN, ROGERS K and HERITAGE G (1997) Linking riparian vegetation types and fluvial geomorphology along the Sabie River within the Kruger National Park, South Africa. <i>African Journal of Ecology</i> 35 (3) 194-212.
NICHOLAS AP and WALLING DE (1996) The significance of particle aggregation in the overbank deposition of suspended sediment on river floodplains. <i>Journal of Hydrology</i> 186 (1-4) 275-293.
HOOKE JM (1979) An analysis of the processes of river bank erosion. <i>Journal of Hydrology</i> 42 (1-2) 39-62.</td></tr>
</table>

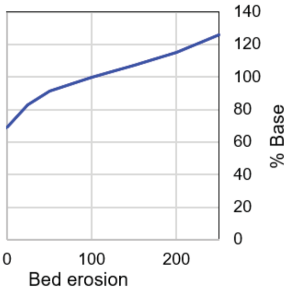
3.3.7 Bed sediment size

Bed sediment conditions within the active channel may coarsen or fine. An increase in the indicator represents an increase in sediment size or a coarsening of the bed sediment (Table 3.9):

Purpose: Aquatic organisms require specific bed grain-sizes for nesting or other life stages. Very fine bed sediment has the potential to clog interstitial spaces leading to a reduction in available habitat.

Links: Bed erosion.

Table 3.9 Bed sediment size links, explanations and supporting literature

<table>
<tr><th colspan="2">BED SEDIMENT SIZE</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Bed erosion [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.8</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.1</td></tr>
<tr><td>Max</td><td>250</td><td>1.55</td></tr>
</table>


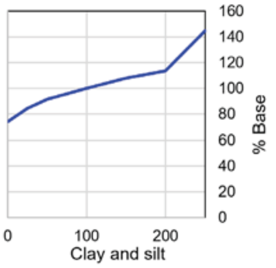
</td><td>Bed erosion: Increased erosion will winnow finer material from the bed of the river and increase the median grain size of the channel. A reduction in bed erosion will promote the deposition of finer grained material and reduce the median bed sediment grain-size. (Alekseevskiy 2008)</td></tr>
<tr><td colspan="2">ALEKSEEVSKIY NI, BERKOVICH KM and CHALOV RS (2008) Erosion, sediment transportation and accumulation in rivers. <i>International Journal of Sediment Research</i> 23 (2) 93-105.</td></tr>
</table>

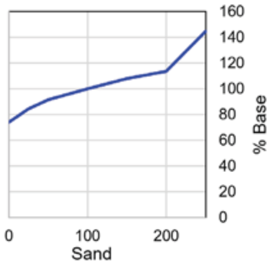
3.3.8 Embeddedness

Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered, or sunken into the silt, sand, or mud of the riverbed (Table 3.10):

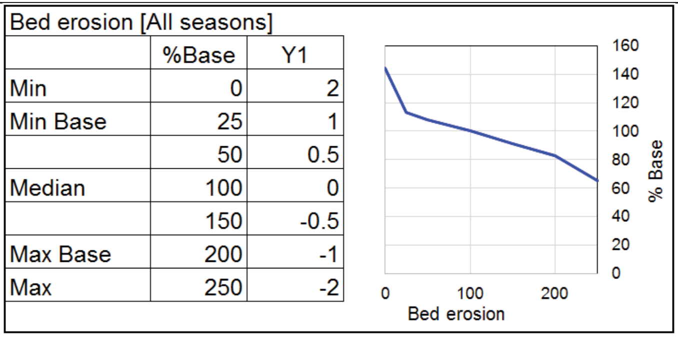
Purpose:	As rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning and egg incubation.
Links:	Clay and silt; Sand; Bed erosion.

Table 3.10 Embeddedness links, explanations and supporting literature

<table>
<tr><th colspan="2">EMBEDDEDNESS</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Clay and silt [D season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.9</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.0</td></tr>
<tr><td>Max</td><td>250</td><td>2.0</td></tr>
</table>


</td><td>Clay and silt: Increased fine material in the system will drive sedimentation and embeddedness (Sennatt <i>et al.</i> 2006)</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Sand [T2 season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.9</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.0</td></tr>
<tr><td>Max</td><td>250</td><td>2.0</td></tr>
</table>


</td><td>Sand: Increased bedload in the system will drive sedimentation and embeddedness</td></tr>
</table>

<table>
<tr><th colspan="2">EMBEDDEDNESS</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Bed erosion [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>
</td><td>Bed erosion: increases in bed erosion will reduce embeddedness as the finer particles are eroded (Smith 2023).</td></tr>
<tr><td colspan="2">SENNATT KM, SALANT NL, RENSHAW CE and MAGILLIGAN FJ (2006) Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated STREAMS1. <i>Journal of the American Water Resources Association</i> 42 (6) 1671-1682.
SMITH SL (2023) Estimating Embeddedness from Bankfull Shear Velocity in Gravel Streambeds to Assess Sediment Impacts on Aquatic Biota, PhD, Virginia Tech.</td></tr>
</table>

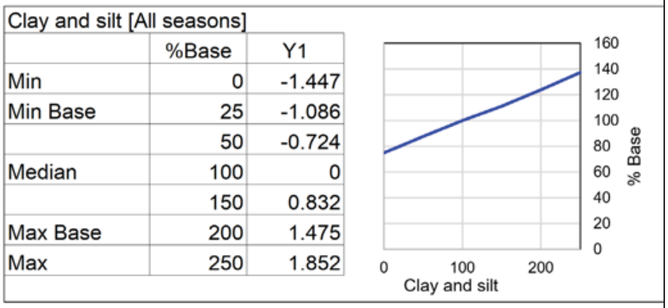
3.3.9 Turbidity

Turbidity is a measure of water clarity, and is related to the potential of the suspended material to diffract light; finer suspended sediments will result in higher turbidity levels as compared to coarser material so this indicator is related to the proportion of the baseline suspended clay and fine sediment (Table 3.11):

Purpose: High turbidity restricts light penetration, reduces visibility which can influence visual feeding, and can clog gills. Indigenous flora and fauna have evolved to live with baseline levels of turbidity.

Links: Clay and silt.

Table 3.11 Turbidity links, explanations and supporting literature

<table>
<tr><th colspan="2">TURBIDITY</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Clay and silt [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>
</td><td>Silt, clay and FPOM: The relationship between suspended sediment load and increasing turbidity is almost 1:1, with an increase in concentration of fine sediments resulting in a similar increase in turbidity levels. In general, assuming grain size remains uniform, turbidity relates linearly to suspended material (Bright <i>et al.</i> 2020). This correlation is particularly strong for rivers where suspended loads characterise the basin (Truhlar 1978).</td></tr>
<tr><td colspan="2">BRIGHT C, MAGER S and HORTON S (2020) Response of nephelometric turbidity to hydrodynamic particle size of fine suspended sediment. <i>International Journal of Sediment Research</i> 35 (5) 444-454.
TRUHLAR JF (1978) Determining suspended sediment loads from turbidity records. <i>Hydrological Sciences Journal</i> 23 (4) 409-417.</td></tr>
</table>

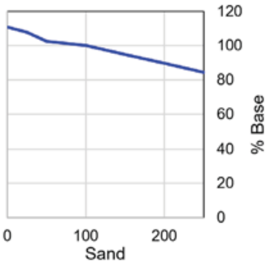
3.3.10 *Pool depth*

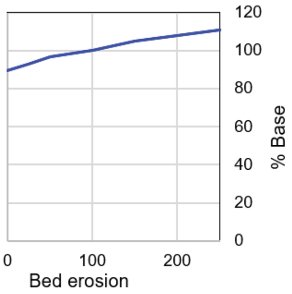
Is the morphological depth of pools in the dry season as a result of erosion or deposition which has an influence on the depth of water (Table 3.12). Deep pools are important as refugia for fish and other aquatic organisms during periods of low flow:

Purpose: Pools provide important habitat for fish, acting as refuge and resting areas.

Links: Sand; Bed erosion.

Table 3.12 Pool depth links, explanations and supporting literature

<table>
<tr><td colspan="2">POOL DEPTH</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Sand [D season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>0.8</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.6</td></tr>
<tr><td>Max</td><td>250</td><td>-0.9</td></tr>
</table>


</td><td>Sand: Pool depth responds to sediment loads (Lisle and Hilton 1992). The higher the sediment loads the higher the potential for sedimentation to reduce pool depth.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Bed erosion [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-0.6</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.4</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>0.8</td></tr>
</table>


</td><td>Bed erosion: Pool depth will increase with erosion (Kuhnle 1996).</td></tr>
<tr><td colspan="2">LISLE TE and HILTON S (1992) The Volume of Fine Sediment In Pools: An Index Of Sediment Supply In Gravel-Bed Streams 1. <i>JAWRA Journal of the American Water Resources Association</i> 28 (2) 371-383.
KUHNLE RA, BINGNER RL, FOSTER GR and GRISSINGER EH (1996) Effect of land use changes on sediment transport in Goodwin Creek. <i>Water Resources Research</i> 32 (10) 3189-3196.</td></tr>
</table>

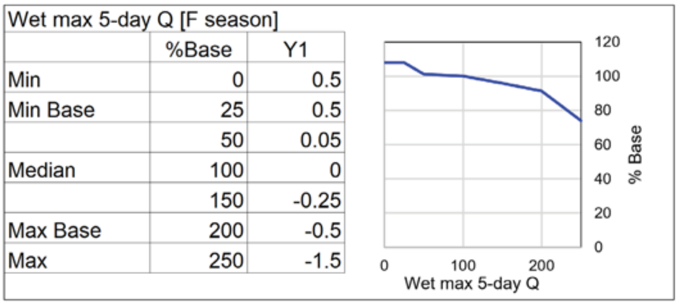
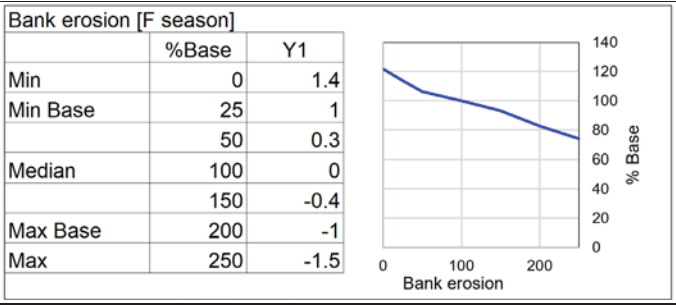
3.3.11 *Cut banks*

Cut and vertical banks are important features that create deeper sections of the channel adjacent to the steep banks and are often associated with marginal overhanging vegetation and provide nesting habitat for birds and other animals (Table 3.13). The indicator measures the structural stability of cut banks with usable habitat and not unstable cut banks created by bank slumping and rapid bank retreat. The loss of habitat due to erosion and bank retreat is quantified in the Bank erosion indicator:

Purpose: Cut banks are important habitat for invertebrates, birds, and other animals.

Links: Wet max 5-day Q; Bank erosion.

Table 3.13 Cut banks links, explanations and supporting literature

<table>
<tr><th colspan="2">CUT BANKS</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet max 5-day Q [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.05</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.25</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>
</td><td>Wet max 5-day Q: Very large floods redistribute sediment across the channel and tend to replenish the marginal zones with sediment (reducing the extent of cut banks). Average floods could be expected to have little net impact, and very low floods may cause some incision of the low channel and undercut the marginal areas, increasing the extent of cut banks.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Bank erosion [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.4</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>
</td><td>Bank erosion: Erosion will remove the cut banks with suitable habitat (Allmendinger <i>et al.</i> 2005)</td></tr>
<tr><td colspan="2">ALLMENDINGER NE, PIZZUTO JE, POTTER JRN, JOHNSON TE and HESSION WC (2005) The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. <i>Geological Society of America Bulletin</i> 117 (1-2) 229-243.</td></tr>
</table>

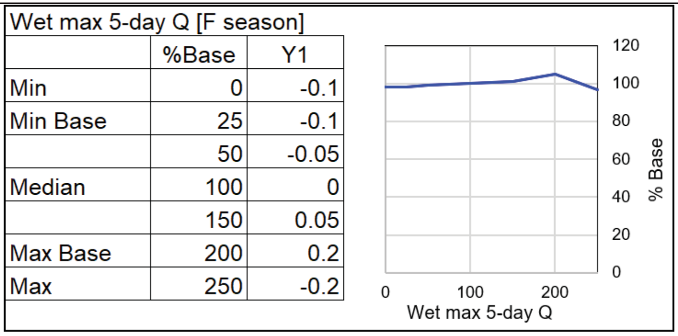
3.3.12 Islands and bars

Consolidated islands / mid-channel bars stand alone, and depending upon their size can have wet and/or dry bank species (Table 3.14):

Purpose: Often islands are less disturbed as compared to the riverbanks and act as refugia for plants and therefore animals.

Links: Wet max 5-day Q; Bank erosion; Wetbank grasses; Agg: Aquatic veg.

Table 3.14 Islands and bars links, explanations and supporting literature

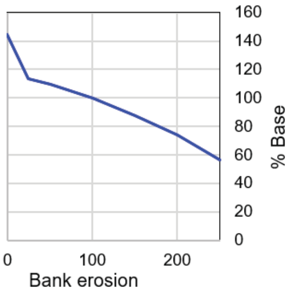
<table>
<tr><th colspan="2">ISLANDS AND BARS</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet max 5-day Q [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.1</td></tr>
<tr><td></td><td>50</td><td>-0.05</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.05</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.2</td></tr>
<tr><td>Max</td><td>250</td><td>-0.2</td></tr>
</table>
</td><td>Wet max 5-day Q: Moderate floods would build the islands (depositing sediment on the margins and in the lee of the islands), whilst extremely large floods would erode the upstream banks.</td></tr>
</table>

ISLANDS AND BARS

Link and response curve | **Explanation and supporting literature**

Bank erosion [F season]

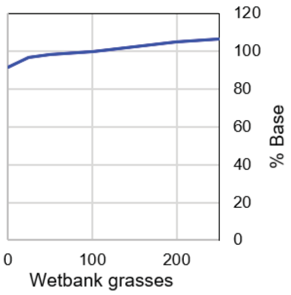
	%Base	Y1
Min	0	2
Min Base	25	1
	50	0.7
Median	100	0
	150	-0.7
Max Base	200	-1.5
Max	250	-2.5



Bank erosion: High bank erosion will remove the sand bars and other substrate underlying vegetated islands; low erosion will allow the development of new bars.

Wetbank grasses [F season]

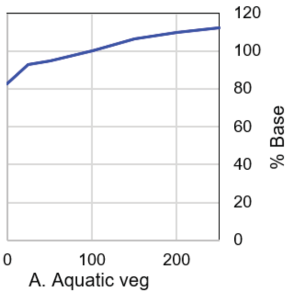
	%Base	Y1
Min	0	-0.5
Min Base	25	-0.2
	50	-0.1
Median	100	0
	150	0.1
Max Base	200	0.2
Max	250	0.3



Wetbank grasses: A good vegetation cover will protect the islands from erosion and encourage deposition. Loss of cover makes the banks prone to erosion.

A. Aquatic veg [F season]

	%Base	Y1
Min	0	-1
Min Base	25	-0.4
	50	-0.3
Median	100	0
	150	0.3
Max Base	200	0.7
Max	250	0.9



Agg: Aquatic veg: One hydraulic impact of aquatic vegetation is an increase in flow resistance and a reduction in conveyance capacity. The aboveground portion of biomass helps increase sedimentation both by reducing the local flow velocities and by providing additional horizontal surface per volume upon which sedimentation can occur (Rominger *et al.* 2010). Increased sedimentation builds islands and bars.

ROMINGER JT, LIGHTBODY AF and NEPF HM (2010) Effects of Added Vegetation on Sand Bar Stability and Stream Hydrodynamics. Journal of Hydraulic Engineering **136** (12) 994-1002.

3.3.13 Backwaters and secondary channels

The area of backwaters and secondary channels reflects the availability of inundated, low velocity, shallow marginal and/or secondary channels and backwaters (Table 3.15):

Purpose: Secondary channels and backwaters provide aquatic refuge habitat in the form of low or no velocity areas.

Links: Dry min 5-day Q; Wet max 5-day Q.

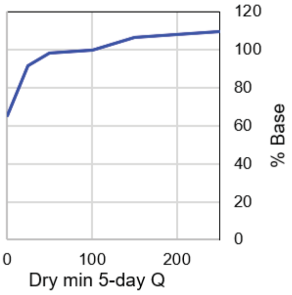
Table 3.15 Backwaters and secondary channels links, explanations and supporting literature

BACKWATERS AND SECONDARY CHANNELS

Link and response curve

Dry min 5-day Q [D season]

	%Base	Y1
Min	0	-2
Min Base	25	-0.5
	50	-0.1
Median	100	0
	150	0.3
Max Base	200	0.5
Max	250	0.7

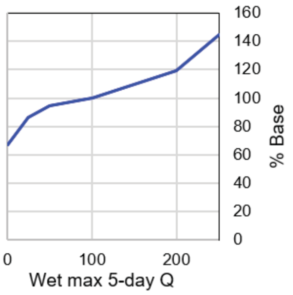


Explanation and supporting literature

Dry min 5-day Q: Backwaters can be created in the low flow season, with increases in dry season flows, a greater proportion of marginal habitat (active channel width) is engaged (Goudie 2004; Hugget and Shuttleworth 2022). Higher dry season flows are also important because they will maintain backwaters and pools through sub-surface flow.

Wet max 5-day Q [F season]

	%Base	Y1
Min	0	-1.9
Min Base	25	-0.8
	50	-0.3
Median	100	0
	150	0.7
Max Base	200	1.3
Max	250	2



Wet max 5-day Q: The higher the maximum flows in the river, the greater the extent of inundation of the backwaters. Lower peak flows will limit the extent of seasonal inundation.

GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.
HUGGETT R and SHUTTLEWORTH E (2022) *Fundamentals of geomorphology*. Taylor and Francis.

3.3.14 Exposed sandy habitat in the dry season

Exposed sandy habitat in the dry season are the sand bars that become exposed during the low flow season and remain exposed for a sufficient duration to be usable habitat (Table 3.16):

Purpose:	Habitat for birds, mammals, and reptiles e.g. crocodiles
Links:	Dry duration; Dry average daily volume; Bed erosion.

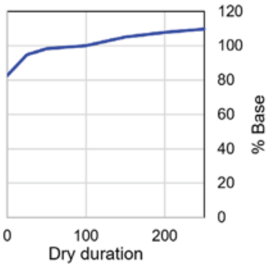
Table 3.16 Exposed sandy habitat in the dry season links, explanations and supporting literature

EXPOSED SANDY HABITAT IN THE DRY SEASON

Link and response curve

Dry duration [D season]

	%Base	Y1
Min	0	-1
Min Base	25	-0.3
	50	-0.1
Median	100	0
	150	0.2
Max Base	200	0.5
Max	250	0.7



Explanation and supporting literature

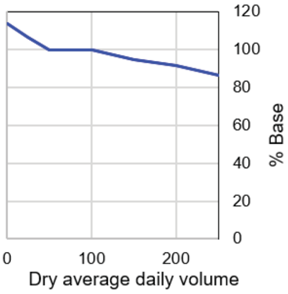
Dry duration: The longer the dry season, the longer the time that the sandy areas are exposed and available for breeding, nesting, foraging, etc.

EXPOSED SANDY HABITAT IN THE DRY SEASON

Link and response curve	Explanation and supporting literature

Dry average daily volume [D season]

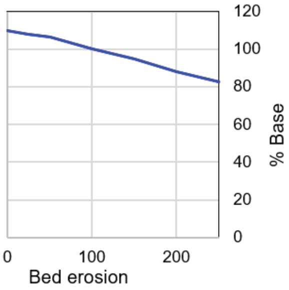
	%Base	Y1
Min	0	1
Min Base	25	0.3
	50	0
Median	100	0
	150	-0.3
Max Base	200	-0.5
Max	250	-0.8



Dry average daily volume: The higher the dry daily average volume the higher the water level and the lower the area of exposed sandy habitat (Goudie 2004).

Bed erosion [All seasons]

	%Base	Y1
Min	0	0.7
Min Base	25	0.5
	50	0.3
Median	100	0
	150	-0.3
Max Base	200	-0.7
Max	250	-1



Bed erosion: Increased bed erosion will remove sand deposits.

GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.

3.3.15 *Exposed cobble habitat in the dry season*

The in-channel cobble and boulder areas that become exposed by low flow during the dry season and remain exposed for a sufficient duration to be usable habitat (Table 3.17):

Purpose:	Habitat for birds and some marginal plant species. The interstitial spaces are also important for insects and reptiles.
Links:	Dry duration; Dry average daily volume; Bed erosion; Cobbles and boulders.

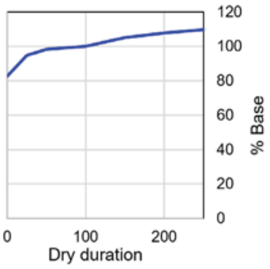
Table 3.17 Exposed cobble habitat in the dry season links, explanations and supporting literature

EXPOSED COBBLE HABITAT IN THE DRY SEASON

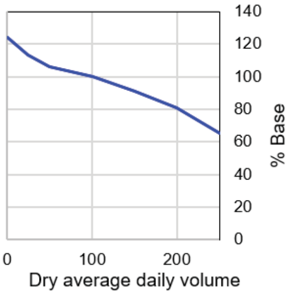
Link and response curve	Explanation and supporting literature

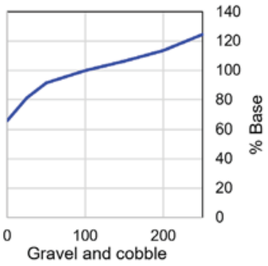
Dry duration [D season]

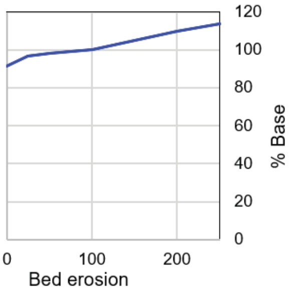
	%Base	Y1
Min	0	-1
Min Base	25	-0.3
	50	-0.1
Median	100	0
	150	0.2
Max Base	200	0.5
Max	250	0.7



Dry duration: The longer the dry season, the longer the time that the rocky areas are exposed and available for breeding, nesting, foraging, etc.

<table>
<tr><th colspan="2">EXPOSED COBBLE HABITAT IN THE DRY SEASON</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Dry average daily volume [D season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Dry average daily volume: The higher the dry daily average volume the higher the water level and the lower the area of exposed rocky habitat (Goudie 2004).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Gravel and cobble [F season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Gravel and cobble: Supply of bedload (gravel and cobbles) provides material to build and maintain the cobble habitat.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Bed erosion [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.7</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Bed erosion: Increased erosion will remove sand deposits and expose cobbles.</td></tr>
<tr><td colspan="2">GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.</td></tr>
</table>

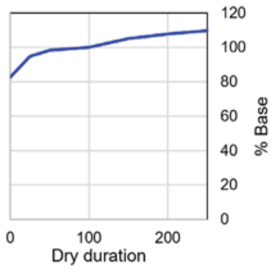
3.3.16 Exposed bedrock habitat in the dry season

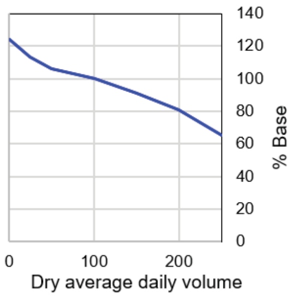
The in-channel bedrock that becomes exposed by low flow during the dry season (Table 3.18):

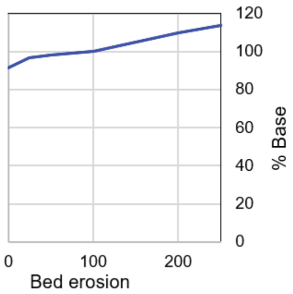
Purpose: Habitat for birds and some marginal plant species

Links: Dry duration; Dry average daily volume; Bed erosion.

Table 3.18 **Exposed bedrock habitat in the dry season links, explanations and supporting literature**

<table>
<tr><th colspan="2">EXPOSED BEDROCK HABITAT IN THE DRY SEASON</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Dry duration [D season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.3</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>0.7</td></tr>
</table>


</td><td>Dry duration: The longer the dry season, the longer the time that the rocky areas are exposed and available for breeding, nesting, foraging, etc. (Goudie 2004).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Dry average daily volume [D season]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Dry average daily volume: The higher the dry daily average volume the higher the water level and the lower the area of exposed rocky habitat (Goudie 2004).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Bed erosion [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.7</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Bed erosion: Increased erosion will remove sand deposits and expose the bedrock.</td></tr>
<tr><td colspan="2">GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.</td></tr>
</table>

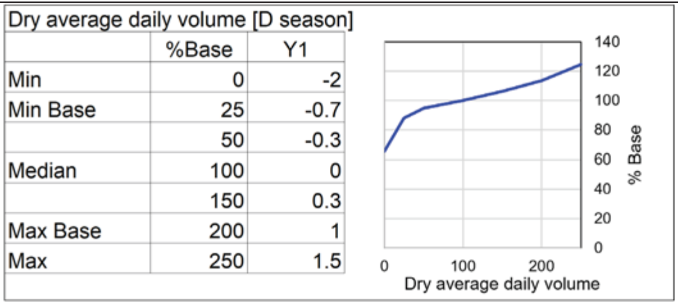
3.3.17 Inundated sandy habitat

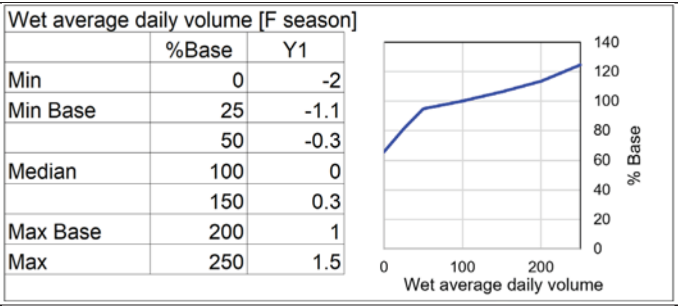
In-channel inundated sand banks and bars / sandy habitat (Table 3.19):

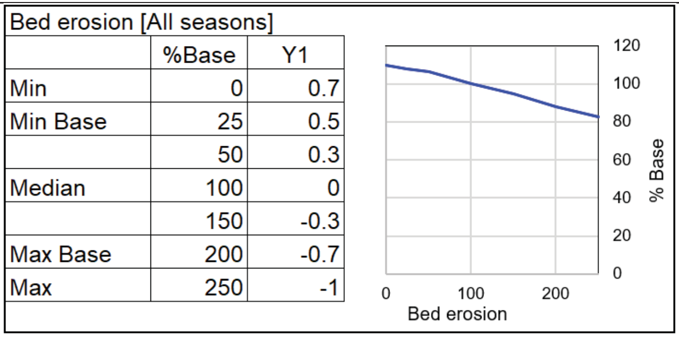
Purpose: Habitat for some invertebrate, fish, and plant species. Important for fish nesting

Links: Dry average daily volume; Wet average daily volume; Bed erosion.

Table 3.19 Inundated sandy habitat links, explanations and supporting literature

<table>
<tr><th colspan="2">INUNDATED SANDY HABITAT</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>

Dry average daily volume [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.7</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Dry average daily volume: The higher the dry season flow, the larger the area of sandy areas inundated (Goudie 2004).</td></tr>
<tr><td>

Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Wet average daily volume: The higher the wet season flow, the larger the area of sandy areas inundated (Goudie 2004). This link Is only for inundation (transport is dealt with by erosion).</td></tr>
<tr><td>

Bed erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.7</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.7</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>

</td><td>Bed erosion: Increased erosion will remove the sand deposits and reduce the availability of sandy areas.</td></tr>
<tr><td colspan="2">GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.</td></tr>
</table>

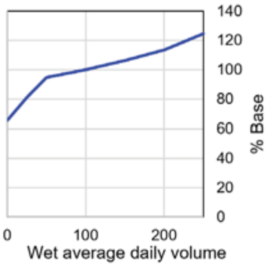
3.3.18 Inundated cobble habitat

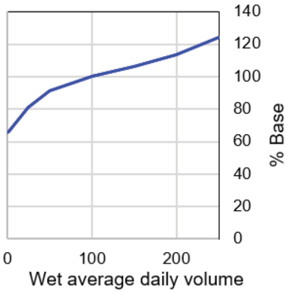
In-channel inundated cobble and boulder habitat (Table 3.20):

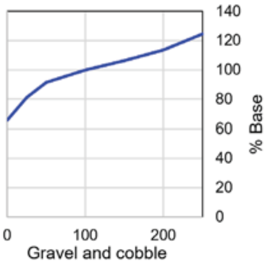
Purpose: Habitat for some macroinvertebrate, fish, and plant species

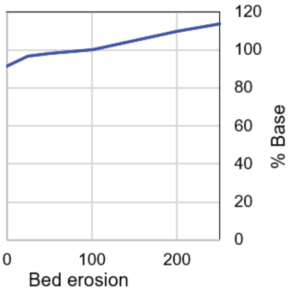
Links: Dry average daily volume; Wet average daily volume; Bed erosion; Gravel and cobble.

Table 3.20 Inundated cobble habitat links, explanations and supporting literature

<table>
<tr><th colspan="2">INUNDATED COBBLE HABITAT</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet average daily volume [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Dry average daily volume: The higher the dry season flow, the larger the area of rocky areas inundated (Goudie 2004).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Wet average daily volume [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Wet average daily volume: The higher the dry season flow, the larger the area of rocky areas inundated (Goudie 2004). This link is only for inundation (transport is dealt with by erosion).</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Gravel and cobble [F season]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Gravel and cobble: Supply of bedload (gravel and cobbles) provides material to build and maintain the cobble habitat.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Bed erosion [All seasons]</th></tr>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.7</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Bed erosion: Increased erosion will remove the overlying sand deposits and expose cobble habitat.</td></tr>
<tr><td colspan="2">GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.</td></tr>
</table>

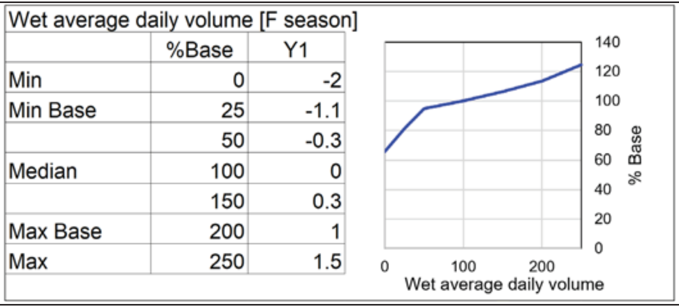
3.3.19 Inundated bedrock habitat

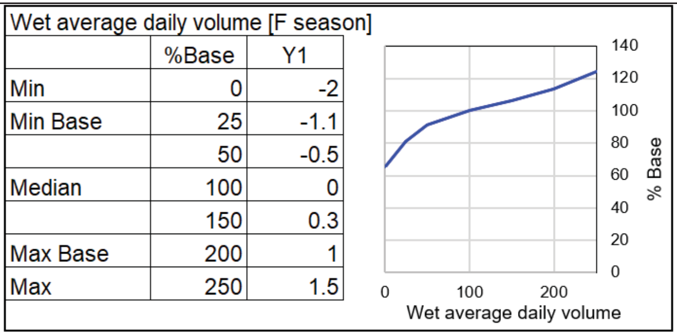
In-channel inundated bedrock habitat (Table 3.21):

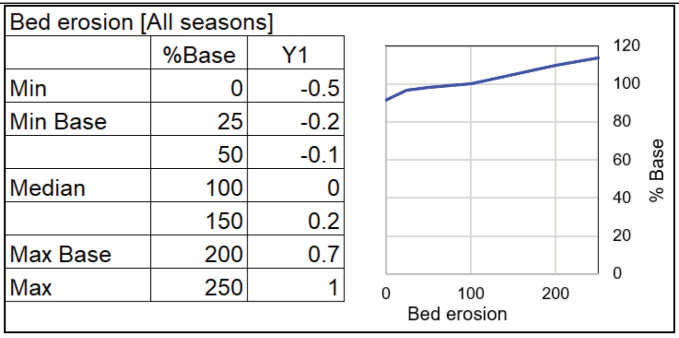
Purpose: Habitat for some macroinvertebrate, fish, and plant species

Links: Dry average daily volume; Wet average daily volume; Bed erosion.

Table 3.21 Inundated bedrock habitat links, explanations and supporting literature

<table>
<tr><th colspan="2">INUNDATED BEDROCK HABITAT</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>


Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Dry average daily volume: The higher the dry season flow, the larger the area of rocky areas inundated (Goudie 2004).</td></tr>
<tr><td>


Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Wet average daily volume: The higher the dry season flow, the larger the area of rocky areas inundated (Goudie 2004). This link is only for inundation (transport is dealt with by erosion).</td></tr>
<tr><td>


Bed erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.2</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.7</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>
</td><td>Bed erosion: Increased erosion will remove the overlying sand deposits and expose the bedrock.</td></tr>
<tr><td colspan="2">GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.</td></tr>
</table>

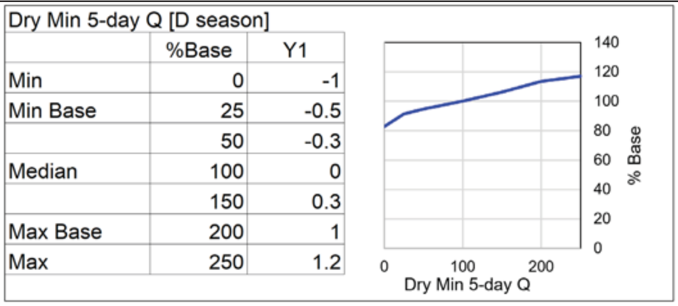
3.3.20 Riffles

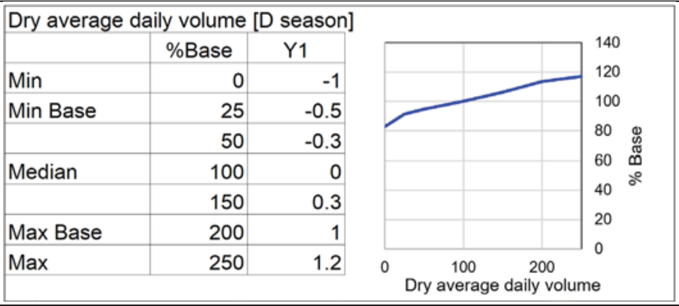
Riffles are shallower faster moving sections of rivers where rocks break the water surface (Table 3.22):

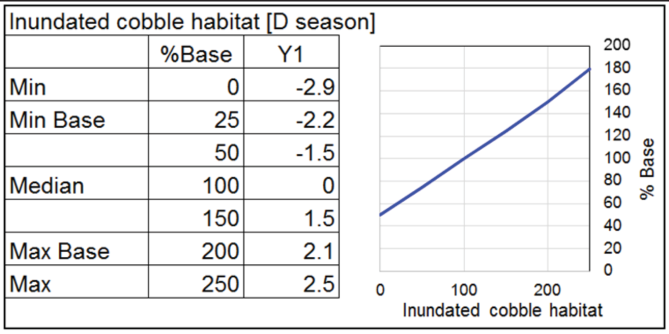
Purpose: Riffles are important fish habitat. As water rushes over the rocks it adds oxygen to the water. Insects that live in the water need oxygen, so they like to live in the riffles. Fish can find food to eat in riffles.

Links: Dry min 5-day Q / Dry average daily volume; Inundated cobble habitat.

Table 3.22 Riffles links, explanations and supporting literature

<table>
<tr><th colspan="2">RIFFLES</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>

Dry Min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.2</td></tr>
</table>

</td><td>Dry min 5-day Q: Reductions in the dry season average depth will reduce the extent of riffles.</td></tr>
<tr><td>

Dry average daily volume [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.3</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.2</td></tr>
</table>

</td><td>Dry average daily volume: Reductions in the dry season average depth will reduce the extent of riffles.</td></tr>
<tr><td>

Inundated cobble habitat [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.9</td></tr>
<tr><td>Min Base</td><td>25</td><td>-2.2</td></tr>
<tr><td></td><td>50</td><td>-1.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.1</td></tr>
<tr><td>Max</td><td>250</td><td>2.5</td></tr>
</table>

</td><td>Inundated cobble habitat: Reductions in the inundated cobble habitat will reduce the extent of riffle habitat available.</td></tr>
</table>

3.4 Algae

3.4.1 Filamentous algae

Filamentous algae (Table 3.23) are colonial and contain chloroplasts with chlorophyll a and b (Bell 1992). Unlike algal biofilms, they are unpalatable and do not form a component of the food source periphyton (Ewart-Smith 2013):

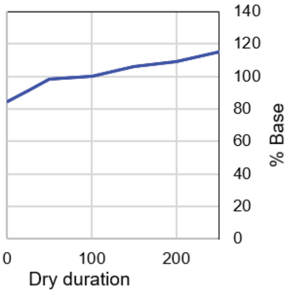
Habitat: Filamentous algae grow on the channel bed, be it rocky or sandy, and in aquatic vegetation (Biggs 1995).

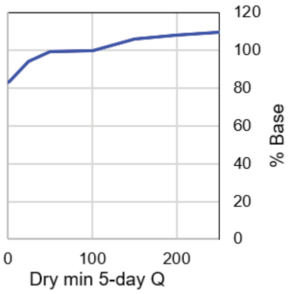
Growth: Unlike algal biofilms, they are favoured under conditions of increased light, temperature and/or nutrients (Hill 1996, Wilde and Tilly 1981) and are slower to recover from the disturbances associated with floods (Ewart-Smith 2013).

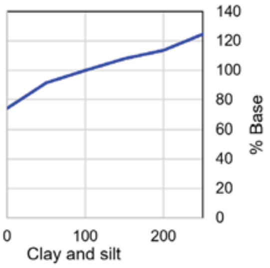
Reproduction: Filamentous algae respond quickly to changes in temperature and nutrients and grow at any time of the year (Ewart-Smith 2013).

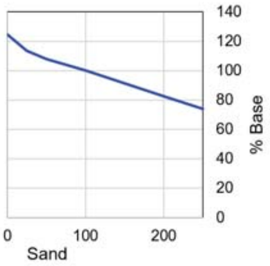
Links: Dry duration; Dry min 5-day Q; Bed erosion; Clay and silt; Sand; Bed erosion; Turbidity.

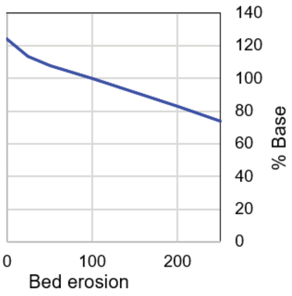
Table 3.23 Filamentous algae links, explanations and supporting literature

<table>
<tr><th colspan="2">FILAMENTOUS ALGAE</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.9</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.28</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.65</td></tr>
<tr><td>Max</td><td>250</td><td>1.1</td></tr>
</table>


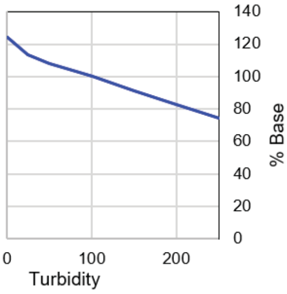
</td><td>Dry duration: Filamentous algae grow best in the dry season (Ewart-Smith 2013), a longer dry season favours growth.</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.33</td></tr>
<tr><td></td><td>50</td><td>-0.03</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.27</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>0.7</td></tr>
</table>


</td><td>Dry min 5-day Q: Filamentous algae grow on the channel bed, rock or sand, and in aquatic vegetation (Biggs 1995). At lower discharges less habitat is available. Greater dry season discharges inundate more habitat.</td></tr>
<tr><td>
Clay and silt [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Filamentous algae grow better with more nutrients (Hill 1996, Wilde and Tilly 1981). More clay and silts will bring more nutrients.</td></tr>
<tr><td>
Sand [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Sand: Sediment load (sand) disturbs filamentous algae (Holomuzki and Biggs 2006) and scours it (Biggs and Thomsen 1995) from wet rocky habitat.</td></tr>
<tr><td>
Bed erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bed erosion: Erosion of the channel bed scours bed sediments (Holomuzki and Biggs 2006) and filamentous algae (Biggs and Thomsen 1995).</td></tr>
</table>

<table>
<tr><th colspan="2">FILAMENTOUS ALGAE</th></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Turbidity [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>

</td><td>Turbidity: Turbidity decreases light penetration; reduced light into the water column decreases growth and therefore biomass of filamentous algae (Hill 1996).</td></tr>
<tr><td colspan="2">BIGGS BJF (1995) The contribution of disturbance, catchment geology and landuse to the habitat template of periphyton in stream ecosystems. <i>Freshwater Biology</i> 33 419-438.
BIGGS BJF and THOMSEN HA (1995) Disturbance of stream periphyton by pertubations in shear stress: Time to structural failure and differences in community resistance. <i>Journal of Phycology</i> 31 233-241.
EWART-SMITH JL (2013) The relationship between periphyton, flow and nutrients in foothill rivers of the south-western Cape, South Africa. Unpublished PhD thesis, University of Cape Town, Cape Town, South Africa.
HOLOMUZKI JR and BIGGS BJF (2006) Food limitation affects algivory and grazer perfomance for New Zealand stream macroinvertebrates. <i>Hydrobiologia</i> 561 83-94.
HILL WR (1996) Effects of light. In STEVENSON RH, Bothwell ML and LOWE RL (eds.). <i>Algal Ecology: Freshwater benthic ecosystems</i>. Academic Press, San Diego. 121-148 pp.
WILDE EW and TILLY LJ (1981) Structural characteristics of algal communities in thermally altered artificial streams. <i>Hydrobiologia</i> 76 57-63.</td></tr>
</table>

3.4.2 Algal biofilms

In freshwater, algal biofilms comprise predominantly diatoms (Osorio *et al.* 2021), which are unicellular algae (Bacillariophyta, Bell 1992) that together with other algae form a component of the periphyton that grow submerged on the channel bed (Ewart-Smith 2013). Algal biofilms convert dissolved nutrients into a food source for other aquatic organisms (Biggs 1995) and are grazed by snails (Rosemund *et al.* 1993), aquatic macroinvertebrates (Steinman *et al.* 1991), crustaceans (Pringle *et al.* 1993), tadpoles (Petersen and Boulton 1999) and fish (Power and Mathews 1983):

Habitat: Algal biofilms grow on inundated rocky habitat (Ewart-Smith 2013).

Growth: Algal biofilms grow well under conditions of low nutrients, light and temperature and are primarily controlled by changes in flow (Ewart-Smith 2013). Floods disturb algal biofilms in a number of ways. They turn rocks over (Grimm and Fisher 1989); they transport suspended sediments that scour algal biofilms from the rocks (Webb *et al.* 2006) and shear stress also scour algal biofilms from the rocks (Biggs and Thomsen 1995). Flood disturbances override any positive effects of nutrients, temperature or light. A low but constant biomass can persist under conditions of frequent flooding (up to 10 days) as algal biofilms are constantly scoured/flushed away and thus prevented from accruing biomass (Biggs 1995).

Reproduction: Algal biofilms proliferate during the dry season when current velocities are low and if these periods persist for longer than 1-month different successional communities of Algal biofilms may develop (Yang *et al.* 2009).

Links: Dry duration; Dry min 5-day Q; Bed erosion; Turbidity; Inundated cobble habitat OR Inundated bedrock habitat; Filamentous Algae (Table 3.24).

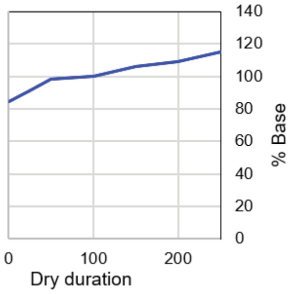
Table 3.24 Algal biofilms links, explanations and supporting literature

ALGAL BIOFILMS

Link and response curve | **Explanation and supporting literature**

Dry duration [D season]

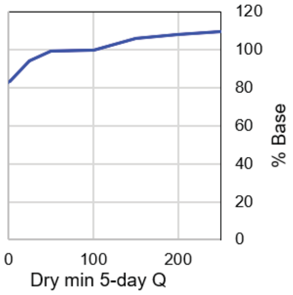
	%Base	Y1
Min	0	-0.9
Min Base	25	-0.5
	50	-0.1
Median	100	0
	150	0.275
Max Base	200	0.65
Max	250	1.1



Dry duration: Algal biofilms grow rapidly in the dry season, a longer dry season favours growth (Ewart-Smith 2013).

Dry min 5-day Q [D season]

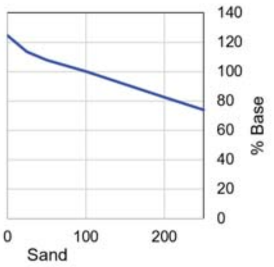
	%Base	Y1
Min	0	-1
Min Base	25	-0.33
	50	-0.03
Median	100	0
	150	0.27
Max Base	200	0.5
Max	250	0.7



Dry min 5-day Q: Algal biofilms grow when submerged (Biggs 1995); larger discharge in the dry season inundates more rocky benthic habitat. Lower discharges reduce the available habitat.

Sand [All seasons]

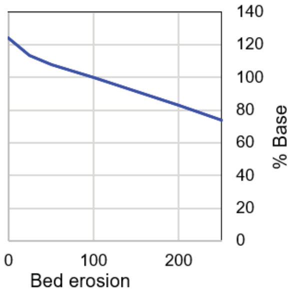
	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.5
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-1.5



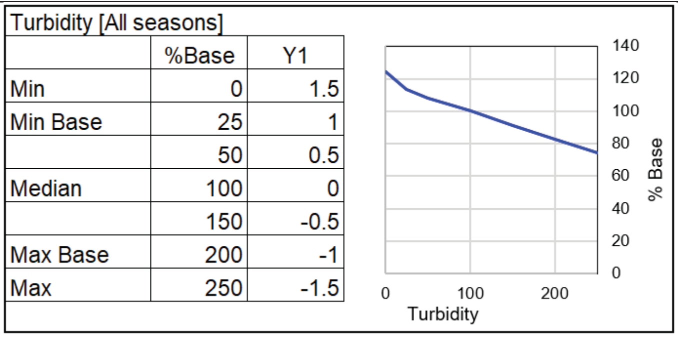
Sand: Sand sediments disturbs algal biofilms (Holomuzki and Biggs 2006) and scours it (Biggs and Thomsen 1995) from inundated rocky habitat.

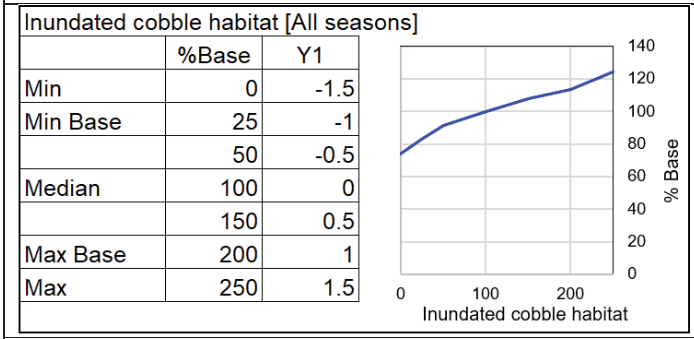
Bed erosion [All seasons]

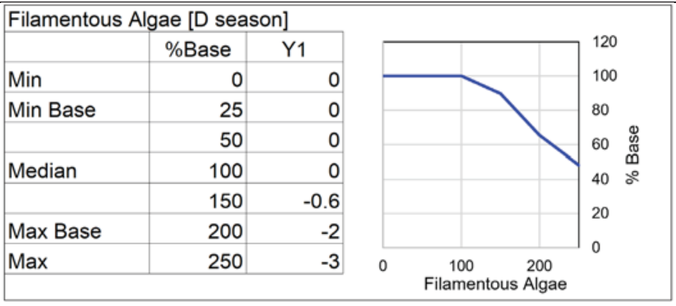
	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.5
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-1.5



Bed erosion: Erosion of the channel bed turns rocks over, disturbing algal biofilms (Holomuzki and Biggs 2006) and scouring them (Biggs and Thomsen 1995).

<table>
<tr><th colspan="2">ALGAL BIOFILMS</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>

Turbidity [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>

</td><td>Turbidity: Turbidity decreases light penetration; reduced light into the water column decreases growth of algal biofilms and therefore biomass (Hill 1996).</td></tr>
<tr><td>

Inundated cobble habitat [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Inundated cobble habitat OR Inundated bedrock habitat: Algal biofilms grow on inundated cobble habitat. More inundated rocky habitat means more Algal biofilms.</td></tr>
<tr><td>

Filamentous Algae [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0</td></tr>
<tr><td>Min Base</td><td>25</td><td>0</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>-2</td></tr>
<tr><td>Max</td><td>250</td><td>-3</td></tr>
</table>

</td><td>Filamentous Algae: As the abundance of filamentous algae increases through succession, the biofilm will decline with an increase in the development of filamentous taxa.</td></tr>
<tr><td colspan="2">BIGGS BJF (1995) The contribution of disturbance, catchment geology and landuse to the habitat template of periphyton in stream ecosystems. <i>Freshwater Biology</i> 33 419-438.
BIGGS BJF and THOMSEN HA (1995) Disturbance of stream periphyton by pertubations in shear stress: Time to structural failure and differences in community resistance. <i>Journal of Phycology</i> 31 233-241.
EWART-SMITH JL (2013) The relationship between periphyton, flow and nutrients in foothill rivers of the south-western Cape, South Africa. Unpublished PhD thesis, University of Cape Town, Cape Town, South Africa.
HILL WR (1996) Effects of light. In STEVENSON RH, Bothwell ML and LOWE RL (eds.). <i>Algal Ecology: Freshwater benthic ecosystems</i>. Academic Press, San Diego. 121-148 pp.
HOLOMUZKI JR and BIGGS BJF (2006) Food limitation affects algivory and grazer perfomance for New Zealand stream macroinvertebrates. <i>Hydrobiologia</i> 561 83-94.</td></tr>
</table>

3.5 Riverine vegetation

3.5.1 Aquatic plants on rock

Aquatic plants grow attached to wet rocky habitat in the channel (Table 3.25). Bryophtyes have been chosen as an example to represent this guild. Bryophytes are small flowerless plants that do not have vascular tissue and grow in the channel on permanently inundated rocks (Bell 1992):

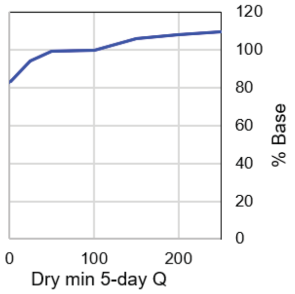
Habitat: Bryophytes attach directly to large substrates and require long periods of substrate stability to establish (Englund 1991). The frequency of inundation at bankfull discharge does not influence bryophytes (Suren and Duncan 1999), rather their distribution is associated with substrate stability, the key driver separating habitats for bryophytes from aquatic macrophytes, which grow in gravels and sands (Chambers *et al.* 1991).

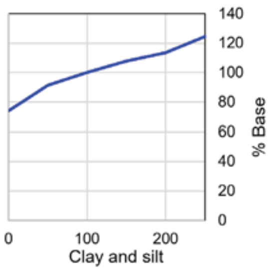
Growth: Bryophytes are well adapted to the forces of flowing water (Miler *et al.* 2012) and tend to dominate in habitats characterised by high flow velocities (Vanderpoorten and Klein 2000).

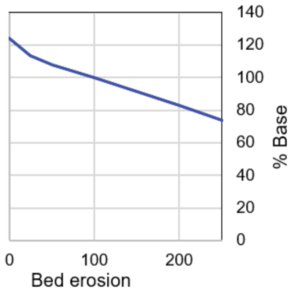
Dispersal: Bryophytes can only reproduce sexually in water. They are drought intolerant and dry out when exposed, but can regenerate when submerged again (Bell 1992).

Links: Dry min 5-day Q; Bed erosion; Turbidity; Inundated cobble habitat OR Inundated bedrock habitat; Clay and silt.

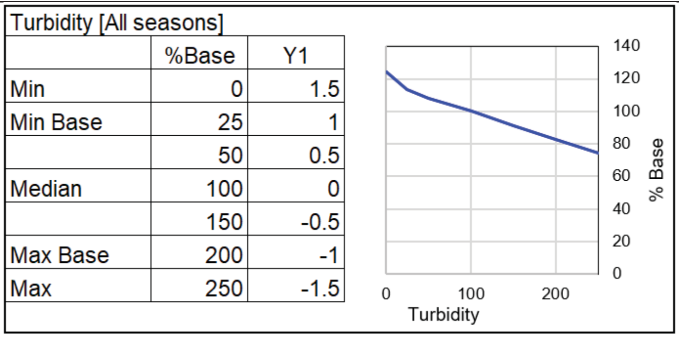
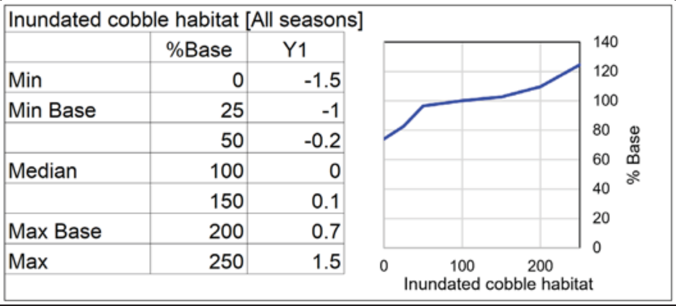
Table 3.25 Aquatic plants on rock links, explanations and supporting literature

<table>
<tr><td>AQUATIC PLANTS ON ROCK</td><td>Indicator Division: <i>Bryophyta</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.33</td></tr>
<tr><td></td><td>50</td><td>-0.03</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.27</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>0.7</td></tr>
</table>


</td><td>Dry min 5-day Q: Bryophytes are drought intolerant and dry out when exposed; the plants do regenerate when inundated again (Bell 1992). Higher discharge in the dry season inundates more bryophytes that grow and spread.</td></tr>
<tr><td>
Clay and silt [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Bryophytes, like all aquatic plants, take nutrients up out of the water (The 2HR Aquarist 2023). More nutrients mean more growth.</td></tr>
<tr><td>
Bed erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bed erosion: Bryophytes are well adapted to fast flowing water and their abundance and distribution is associated with substrate stability (Chambers <i>et al.</i> 1991). More erosion of the channel bed turns stones over and reduces bryophyte abundance.</td></tr>
</table>

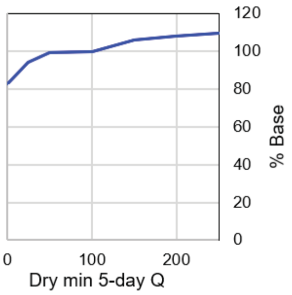
<table>
<tr><td>AQUATIC PLANTS ON ROCK</td><td>Indicator Division: <i>Bryophyta</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Turbidity [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>
</td><td>Turbidity: Bryophytes are slow growing and can only grow and reproduce in the water (Bell 1992). Higher turbidity reduces photosynthesis, growth and reproduction.</td></tr>
<tr><td>
Inundated cobble habitat [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.7</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Inundated cobble habitat OR Inundated bedrock habitat: Bryophytes grow on wet rocks in the channel and require stable rocks for long periods to establish (Englund 1991). More wet rocky habitat increases bryophyte habitat.</td></tr>
<tr><td colspan="2">BELL PR (1992) Green plants. Their origin and diversity. Dioscorides and Press, North America.
CHAMBERS PA, PREPAS EE, HAMILTON HR and BOTHWELL ML (1991) Current velocity and its effect on aquatic macrophytes in flowing water. <i>Ecological applications</i> 1 249-257.
ENGLUND G (1991) Effects of disturbance on stream moss and invertebrate community structure. <i>Journal of the North American Benthological Society</i> 10 143-153.
THE 2 HR AQUARIST (2023) Nutrient uptake through leaves? https://www.2hraquarist.com/blogs/hot-topics/nutrient-uptake-through-leaves, downloaded 26 April 2023.</td></tr>
</table>

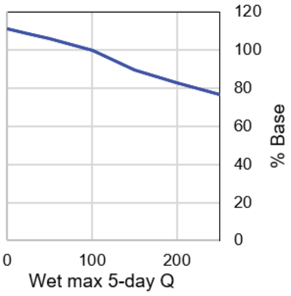
3.5.2 Aquatic plants in sand

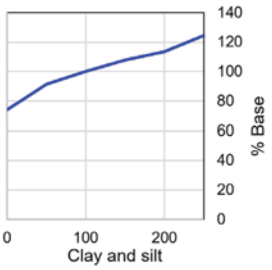
Aquatic plants grow rooted into the bed of backwaters with leaves beneath the surface of the water, or up and open at the water surface (Table 3.26). Oxygen weed, *Lagarosiphon ilicifolius,* represents this guild, which provides important habitat for aquatic insects (Phiri *et al.* 2012):

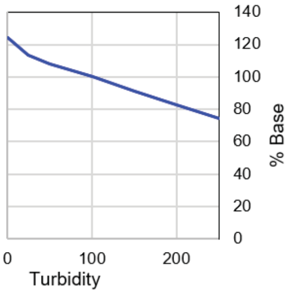
Habitat:	Oxygen weed can grow in a variety of conditions, from very shallow to deep water and in many sediment types. Like most aquatic plants, oxygen weed prefers still or slow-moving water and can be uprooted or break apart when experiencing fast moving water (CABI 2023a).
Growth:	Oxygen weed is a perennial plant, the main growing season is summer (October to February) with extensive branching that takes place, which blocks light to the rooted stems that then break off and create fragment mats that float away (Machena *et al.* 1990). Oxygen weed grows well when there is an excess of nutrients (Wikipedia 2023a).
Dispersal:	Floating plant fragments are able to take root and grow into new plants if they are deposited on a suitable substrate (Phiri *et al.* 2012).
Links:	Dry min 5-day Q; Wet max 5-day Q; Turbidity; Backwaters and secondary channels; Inundated sandy habitat; Clay and silt.

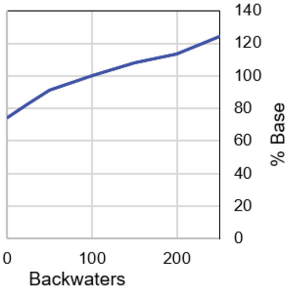
Table 3.26 Aquatic plants in sand links, explanations and supporting literature

<table>
<tr><td>**AQUATIC PLANTS IN SAND**</td><td>Indicator genera: *Nypmhaea* spp.
Lagarosiphon spp., *Trappa* spp.
Potamogeton spp.</td></tr>
<tr><td>**Link and response curve**</td><td>**Explanation and supporting literature**</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.33</td></tr>
<tr><td></td><td>50</td><td>-0.03</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.27</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.5</td></tr>
<tr><td>Max</td><td>250</td><td>0.7</td></tr>
</table>


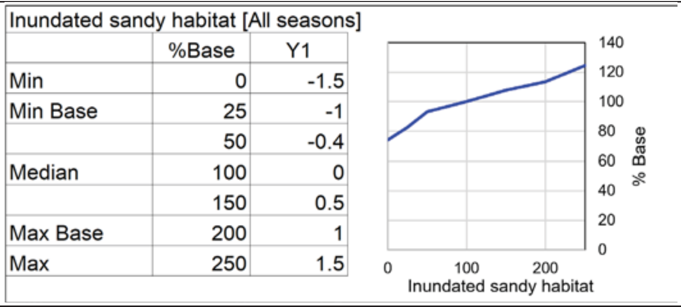
</td><td>Dry min 5-day Q: Lower discharges may strand some plants that can die if stranded for long periods; the plants can withstand stranding for short periods. Flows in the dry season are probably not fast enough to uproot plants or break them apart, so higher dry season discharges support the plants and provide water for vegetative growth.</td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.84</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.6</td></tr>
<tr><td></td><td>50</td><td>0.27</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.61</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.01</td></tr>
<tr><td>Max</td><td>250</td><td>-1.35</td></tr>
</table>


</td><td>Wet max 5-day Q: Aquatic plants in sand prefers still or slow-moving water and can be uprooted or break apart when in fast moving water (CABI 2023a). Higher discharge disturbs plants breaking them apart.</td></tr>
<tr><td>
Clay and silt [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Aquatic plants in sand grow well when there is an excess of nutrients (Wikipedia 2023a). More FPOM means more nutrients.</td></tr>
<tr><td>
Turbidity [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Turbidity: Higher turbidity reduces incident light that hinders photosynthesis and growth of aquatic plants in sand (Bornette and Puijalon 2011).</td></tr>
<tr><td>
Backwaters and secondary channels [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Backwaters and secondary channels: Aquatic plants in sand grow well in the slow flowing backwaters and secondary channels (CABI 2023a). More backwaters and secondary channels provide more habitat for the growth of aquatic plants in sand.</td></tr>
</table>

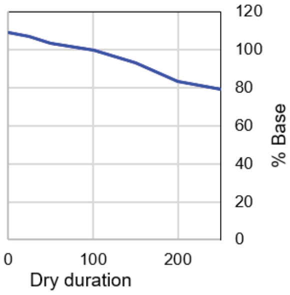
<table>
<tr><td>AQUATIC PLANTS IN SAND</td><td>Indicator genera: <i>Nypmhaea</i> spp.
<i>Lagarosiphon</i> spp., <i>Trappa</i> spp.
<i>Potamogeton</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Inundated sandy habitat [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.4</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Inundated sandy habitat: Aquatic plants in sand can grow in a variety of conditions, from very shallow to deep water and in many sediment types (CABI 2023a). More wet sand means more habitat.</td></tr>
<tr><td colspan="2">BORNETTE G and PUIJALON S (2011) Response of aquatic plants to abiotic factors: a review. <i>Aquatic Science</i> 73 1-4.
CABI (2023a) Commonwealth Agricultural Bureaux International, <i>Lagarosiphon illicifolius,</i> https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.30548, downloaded 27 April 2023.
WIKIPEDIA (2023a) <i>Lagarosiphon major,</i> https://en.wikipedia.org/wiki/Lagarosiphon_major, downloaded 27 April 2023.</td></tr>
</table>

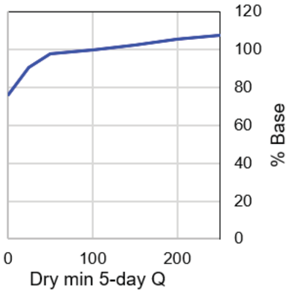
3.5.3 Emergent graminoids

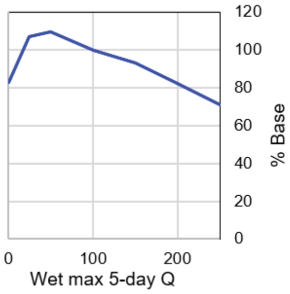
Emergent graminoids are grass like plants in the Families Poaceae (grasses), Cyperaceae (sedges), Juncaceae (rushes) and Typhaceae (bulrushes), which grow rooted in the water with their upright fronds above the water surface. *Vossia cuspidata,* Hippo grass, was chosen as a representative for this guild (Table 3.27). Hippo grass is a rhizomatous perennial with fronds 1-2 m in height above the water's surface and up to 7 m long floating at the surface:

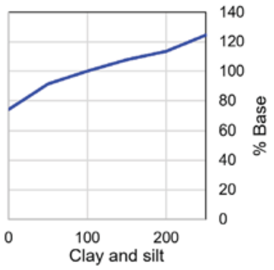
Habitat:	The plants are rooted into the riverbank beneath the surface of the water (Gibbs Russel *et al.* 1990). The plant can survive dry periods for a short period, but persistent drought will cause stress and make the plants susceptible to prolonged grazing that is damaging (Ellenbroek 1987).
Growth:	Hippo grass flowers from Spring to Autumn after the wet season (Gibbs Russel *et al.* 1990). The plants extend their root systems during winter in the dry season (Ellenbroek 1987). Hippo grass grows rapidly in response to an increase in nutrients, for example when nutrient rich silt is deposited onto the riverbank. Low grazed plants are inundated more quickly and for longer and may perish if the aerial leaves of the plant are unable to grow back quickly enough to breach the water's surface (Ellenbroek 1987).
Dispersal:	Hippo grass spreads via pieces of plant stem that are broken off during floods and root themselves as the floods recede (Gibbs Russel *et al.* 1990).
Links:	Dry duration; Dry min 5-day Q; Wet max 5-day Q; Bank erosion; Clay and silt.

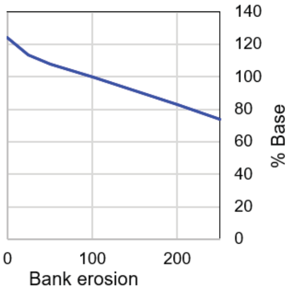
Table 3.27 Emergent graminoids links, explanations and supporting literature

<table>
<tr><td>EMERGENT GRAMINOIDS</td><td>Indicator genera: <i>Vossia</i> spp., <i>Cyperus</i> spp., <i>Juncus</i> spp, <i>Typha</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.63</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.41</td></tr>
<tr><td></td><td>50</td><td>0.14</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.41</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.96</td></tr>
<tr><td>Max</td><td>250</td><td>-1.2</td></tr>
</table>


</td><td>Dry duration: Hippo grass can survive dry periods for a short period, but persistent drought will cause stress and make the grass susceptible to prolonged grazing that is damaging (Ellenbroek 1987).</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.38</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.54</td></tr>
<tr><td></td><td>50</td><td>-0.12</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.22</td></tr>
<tr><td>Max</td><td>250</td><td>0.47</td></tr>
</table>


</td><td>Dry min 5-day Q: Hippo grass extends it root systems during winter in the dry season (Ellenbroek 1987). Higher dry season discharge supports better growth and spread.</td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.37</td></tr>
<tr><td></td><td>50</td><td>0.68</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.03</td></tr>
<tr><td>Max</td><td>250</td><td>-1.67</td></tr>
</table>


</td><td>Wet max 5-day Q: Hippo grass spreads via pieces of stem that break off during floods and take root when deposited onto the wetbank (Gibbs Russel <i>et al.</i> 1990). Higher discharge breaks more stems off reducing abundance.</td></tr>
<tr><td>
Clay and silt [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Hippo grass grows rapidly in response to an increase in nutrients, for example when nutrient rich silt is deposited onto the riverbank (Ellenbroek 1987).</td></tr>
<tr><td>
Bank erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bank erosion: Hippo grass is rooted into the riverbank beneath the surface of the water (Gibbs Russel <i>et al.</i> 1990). Increased bank erosion will disturb and reduce habitat for Hippo grass.</td></tr>
</table>

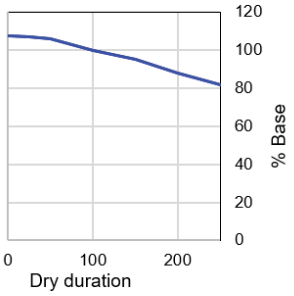
<table>
<tr><td>EMERGENT GRAMINOIDS</td><td>Indicator genera: <i>Vossia</i> spp., <i>Cyperus</i> spp., <i>Juncus</i> spp, <i>Typha</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td colspan="2">ELLENBROEK GA (1987) Ecology and productivity of an African wetland system: The Kafue Flats, Zambia. Dordrecht: Dr. W. Junk.
GIBBS RUSSEL GE, WATSON L, KOEKEMOER M, SMOOK L, BARKER NP, ANDERSON HM, DALLWITZ MJ (1990) Grasses of Southern Africa. Memoirs of the botanical survey of South Africa No. 38. National Botanical Gardens, Botanical Research Institute, South Africa.</td></tr>
</table>

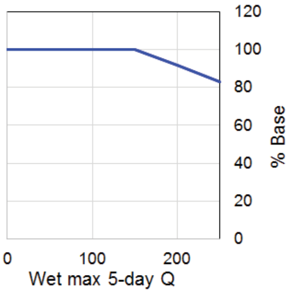
3.5.4 *Wetbank grasses*

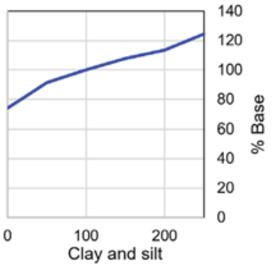
Short grazing grasses, such as *Cynodon dactylon* (Couch grass) and *Stenotaphrum secundatum* (Buffalo grass), often grow as groundcovers on the wetbank (Table 3.28). These two cosmopolitan grasses are very common on riverbanks; *C. dactylon* was chosen as a representative of this guild:

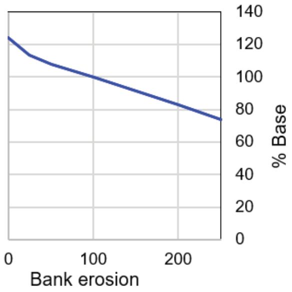
Habitat:	Couch grass is a perennial grass that grows all over the world in a variety of habitats, on almost all soil types, often in moist areas and at disturbed sites (Mudau 2006).
Growth:	Optimal growth occurs during summer; in winter the grass is dormant and turns brown in the cold. Growth is promoted by full sun and retarded by full shade. Additional water encourages growth (Wikipedia 2023b). It grows best in fertile well drained soils, is able to withstand waterlogging, tolerates drought but grows little in dry weather (Useful Temperate Plants Database 2023).
Dispersal:	Couch grass reproduces by seed, or by growth of stolons and rhizomes; the root system may be up to 2 m deep (Wikipedia 2023b).
Links:	Dry duration; Wet max 5-day Q; Bank erosion; Clay and silt.

Table 3.28 Wetbank grasses links, explanations and supporting literature

<table>
<tr><td>WETBANK GRASSES</td><td>Indicator genera: <i>Stenotaphrum</i> spp., <i>Cynodon</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Dry duration [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>0.45</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.41</td></tr>
<tr><td></td><td>50</td><td>0.24</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.27</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.69</td></tr>
<tr><td>Max</td><td>250</td><td>-1.05</td></tr>
</table>

</td><td>Dry duration: Optimal growth occurs during summer; in winter the grass is dormant and turns brown in the cold (Wikipedia 2023b). Couch grass tolerates drought but grows little in dry weather (Useful Temperate Plants Database 2023). A longer dry season means a shorter growing season.</td></tr>
</table>

<table>
<tr><td>WETBANK GRASSES</td><td>Indicator genera: <i>Stenotaphrum</i> spp., <i>Cynodon</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Wet max 5-day Q [F season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>0</td></tr>
<tr><td>Min Base</td><td>25</td><td>0</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.01</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.47</td></tr>
<tr><td>Max</td><td>250</td><td>-0.98</td></tr>
</table>


</td><td>Wet max 5-day Q: Additional water encourages growth (Wikipedia 2023b) and it is able to withstand waterlogging (Useful Temperate Plants Database 2023). At higher discharge plants may be uprooted.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Clay and silt [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Couch grass grows best in fertile well drained soils (Useful Temperate Plants Database 2023). More clay and silt mean more nutrients for better growth.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Bank erosion [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bank erosion: Couch grass grows on the wetbank. Bank erosion will reduce and disturb the wetbank habitat.</td></tr>
<tr><td colspan="2">USEFUL TEMPERATE PLANTS DATABASE (2022) Cynodon dactylon. Creative Commons Attribution-Non Commercial Share Alike 3.0 Unported License. https://temperate.theferns.info/plant/Cynodon+dactylon. Downloaded on 27.09.22.
WIKIPEDIA (2023b) Cynodon dactylon. <https://en.wikipedia.org/wiki/Cynodon_dactylon>. Downloaded on 27 April 2023.</td></tr>
</table>

3.5.5 Papyrus

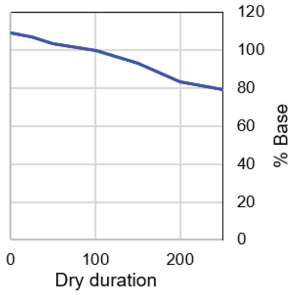
Papyrus (*Cyperus papyrus*) is a tall (4.0 m), coarse grass-like perennial plant that grows as an emergent on the edge of waterways (Table 3.29), or as an amphibious floating sudd (an island comprised of papyrus plants). The plant consists of stout creeping stems and erect triangular stems, leaves are absent and the plant flowers in summer with a green mop-shaped inflorescence (Ellery and Ellery 1997):

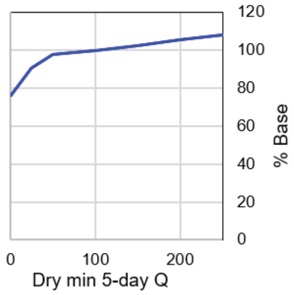
Habitat:	Papyrus grows in full sun in swamps and lakes and can detach from being rooted when inundated to form a floating mass of plants call a sudd (Boar 2006).
Growth:	The plants are dormant in winter and the rhizomes must remain moist to protect them from drying out (Boar 2006).

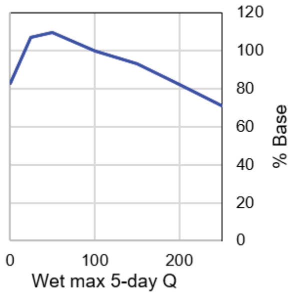
Dispersal: The plant reproduces via the production of fruits in the inflorescences and by the growth of stolons (creeping stems) along the bed. The fruits are distributed by wind and water and the plants are wind pollinated (www.pza.sanbi.org). Seeds germinate best in saturated sediments, poorly in drying sediment and not at all when sediments are flooded (Boar 2006).

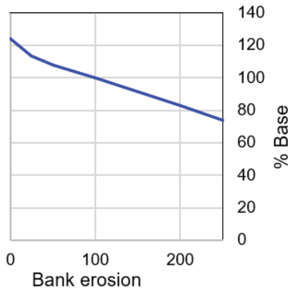
Links: Dry duration; Dry min 5-day Q; Wet max 5-day Q; Bank erosion.

Table 3.29 Papyrus response links, explanations and supporting literature

<table>
<tr><td>PAPYRUS</td><td>Indicator species: <i>Cyperus papyrus</i> (Papyrus).</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.63</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.41</td></tr>
<tr><td></td><td>50</td><td>0.14</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.41</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.96</td></tr>
<tr><td>Max</td><td>250</td><td>-1.2</td></tr>
</table>


</td><td>Dry duration: The plants are dormant in winter so a longer dry season (Boar 2006) means a shorter growing season.</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.38</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.54</td></tr>
<tr><td></td><td>50</td><td>-0.12</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.22</td></tr>
<tr><td>Max</td><td>250</td><td>0.5</td></tr>
</table>


</td><td>Dry min 5-day Q: Papyrus is dormant in the dry season, the plant parts above the surface die back and the plant survives as long as the rhizomes remain moist (van Ginkel <i>et al.</i> 2010). More area of shallow water in the dry season keeps rhizomes moist and alive.</td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.37</td></tr>
<tr><td></td><td>50</td><td>0.68</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.4</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.03</td></tr>
<tr><td>Max</td><td>250</td><td>-1.67</td></tr>
</table>


</td><td>Wet max 5-day Q: Papyrus grows, flowers and fruits in the wet season (Ellery and Ellery 1997). Higher discharge stimulates growth and flowering to a point, above which sudds may become detached and moved downstream. Higher discharge dislodges more papyrus and moves it downstream reducing abundance.</td></tr>
<tr><td>
Bank erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bank erosion: Papyrus grows on the edge of the wet bank. Bank erosion will disturb and reduce habitat for Papyrus.</td></tr>
</table>

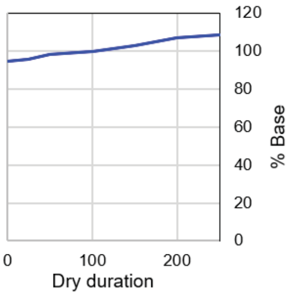
<table>
<tr><td>PAPYRUS</td><td>Indicator species: <i>Cyperus papyrus</i> (Papyrus).</td></tr>
<tr><td colspan="2">BOAR RR (2006) Responses of fringing <i>Cyperus papyrus</i> L. swamp to changes in water level. <i>Aquatic Botany</i> 84 85-92.
ELLERY K, ELLERY F (1997) Plants of the Okavango delta. A field guide. Tsaro publishers, Durban, South Africa.
VAN GINKEL CE, GLEN RP, GORDON-GRAY KD, CILLIERS CJ, MUASYA M and VAN DEVENTER PP (2010) Easy identification of some South African Wetland Plants (grasses, restios, sedges, rushes, bulrushes, eriocaulons and yellow eyed grasses). Water Research Commission Report TT 479/10, Water Research Commission, Pretoria, South Africa. 390 pp.</td></tr>
</table>

3.5.6 Reeds evergreen

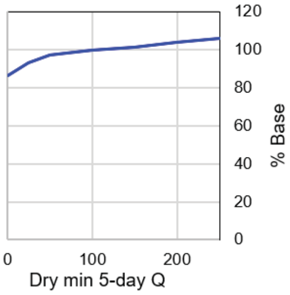
Reed grass (*Phragmites mauritianus*) is an herbaceous perennial with an extensive root system that consolidates and maintains bank stability (Kotschy and Rogers 2008). It is known for its aggressive and persistent survival strategies (Table 3.30):

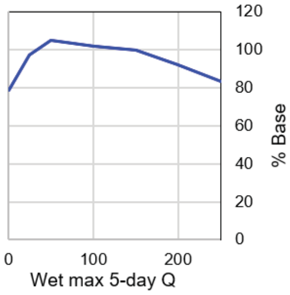
Habitat:	Reed grass grows on the wetbank and is usually a beneficial species controlling erosion (Fanshawe 1972), filtering muddy water and offering a haven to a variety of wildlife. They can grow prolifically and, if not flushed out by floods, can block access to lakes and dams, and block waterways and drainage channels (Bromilow 2010). Reed grass is less tolerant of flooding than Common reed (*Phragmites australis*), and tends to grow higher up in the river where there are rocky foothills and faster flowing water (Kotschy *et al.* 2000).
Growth:	Reed grass will tolerate seasonal drying and can extend rhizomes rapidly along the ground toward new areas of moisture, although expansion is limited by a reduction in expansion and clonal growth. Re-sprouting occurs rapidly after grazing but the plant cannot tolerate prolonged heavy grazing (Kotschy *et al.* 2000).
Dispersal:	Dispersal occurs most successfully via stem fragments broken off from the plant during floods. The plant fragments take root on sandy banks or newly cleared/disturbed areas (Kotschy *et al.* 2000). Reed grass flowers in early spring, fruits in late spring (Fanshawe 1972) and disperses wind borne seeds that are rarely viable. The main means of propagation is almost entirely by vegetative means.
Links:	Dry duration; Dry min 5-day Q; Wet max 5-day Q; Bank erosion; Clay and silt.

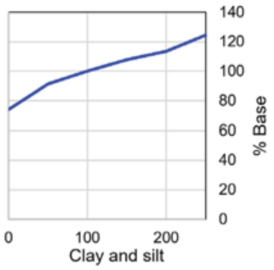
Table 3.30 Reeds evergreen links, explanations and supporting literature

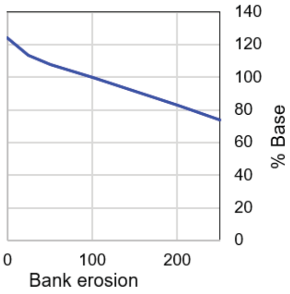
<table>
<tr><td>REEDS EVERGREEN</td><td>Indicator species: <i>Phragmites mauritianus</i> (Reed grass)</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Dry duration [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-0.3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.24</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.12</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.38</td></tr>
<tr><td>Max</td><td>250</td><td>0.59</td></tr>
</table>


</td><td>Dry duration: Reed grass will tolerate seasonal drying and can extend rhizomes rapidly along the ground toward new areas of moisture (Kotschy <i>et al.</i> 2000). A longer dry season means longer time for growth.</td></tr>
</table>

<table>
<tr><td>REEDS EVERGREEN</td><td>Indicator species: Phragmites mauritianus (Reed grass)</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.78</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.39</td></tr>
<tr><td></td><td>50</td><td>-0.17</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.05</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.15</td></tr>
<tr><td>Max</td><td>250</td><td>0.24</td></tr>
</table>


</td><td>Dry min 5-day Q: Reed grass will tolerate seasonal drying and can extend rhizomes rapidly along the ground toward new areas of moisture (Kotschy et al. 2000). Higher discharge in the dry season supports more growth and spread.</td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.23</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.15</td></tr>
<tr><td></td><td>50</td><td>0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0.07</td></tr>
<tr><td></td><td>150</td><td>-0.01</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.47</td></tr>
<tr><td>Max</td><td>250</td><td>-0.98</td></tr>
</table>


</td><td>Wet max 5-day Q: Dispersal occurs most successfully via stem fragments broken off from the plant during floods. The stem fragments take root on sandy banks or newly cleared/disturbed areas (Kotschy et al. 2000). Higher discharge supports growth to a point, after which is negative as more plants are broken down.</td></tr>
<tr><td>
Clay and silt [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Reed grass takes advantage of an increase in nutrients when nutrient rich sediment is deposited on the floodplain (Ellenbroek 1987).</td></tr>
<tr><td>
Bank erosion [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bank erosion: Reed grass grows on the wetbank and is usually a beneficial species controlling erosion (Fanshawe 1972). Increased bank erosion disturbs wetbank habitat reducing spread of Reed grass.</td></tr>
<tr><td colspan="2">
ELLENBROEK GA (1987) Ecology and productivity of an African wetland system: The Kafue Flats, Zambia. Dordrecht: Dr. W. Junk.
FANSHAWE DB (1972) The biology of the reed – Pragmites mauritianus Kunth. Kirkia 8 (2) 147-150.
KOTSCHY KA, ROGERS KH and CARTER AJ (2000) Patterns of change in reed cover and distribution in a seasonal riverine wetland in South Africa. Folia geobotanica 35 (4) 363-373.
</td></tr>
</table>

3.5.7 Wetbank shrubs and trees

Trees and shrubs are common on the wetbank and are adapted to growing with their roots in permanent contact with the water, and with flexible habits that give and bend under the force of large floods (Table 3.31). Willow (*Salix* spp.) and Fig (*Ficus* spp.) trees are two very common genera on the wetbank of SADC rivers. The Safsaf willow, *Salix mucronata,* was selected as the representative for this guild:

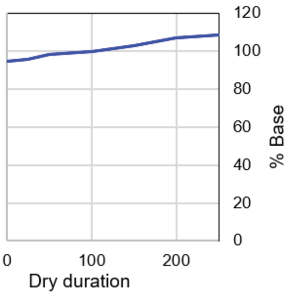
Habitat: The Safsaf willow grows on the wetbank where they access water easily and all year round, and where they get inundated during the wet season (Reinecke 2013).

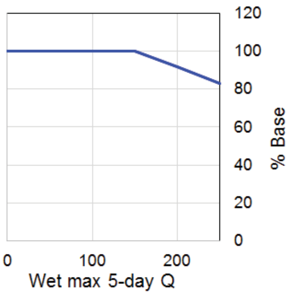
Growth: The Safsaf willow grows as a small evergreen tree or large shrub, with drooping branches off a multi-stemmed trunk. The stems and branches are flexible, moving in the wind and bending with flow when inundated (Reinecke 2013).

Dispersal: Fruits mature in summer over the wet season and open in Autumn, as the floods begin to recede, to release seeds with a silky tuft for wind and water dispersal (Coates Palgrave 1977). The seeds are dispersed by wind along the river corridor in an upstream or downstream direction. The seeds then float once they hit the water's surface and are deposited on the riverbank as the flood waters recede. The seeds germinate and grow into seedlings quickly that take root easily in a variety of different sediments, including nutrient poor sand (PlantZAfrica 2023a). Floods submerge small trees and scour through their canopies breaking off stem fragments that are dispersed downstream, which take root when deposited onto alluvial sand and grow into new trees (Reinecke 2013).

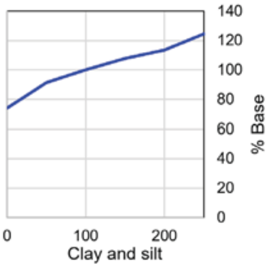
Links: Dry duration, Wet max 5-day Q, Bank erosion, Clay and silt.

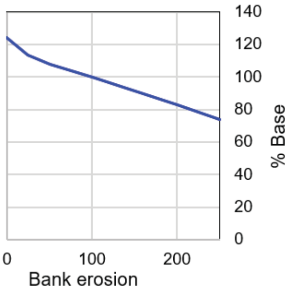
Table 3.31 Wetbank shrubs/trees links, explanations and supporting literature

<table>
<tr><td>WETBANK SHRUBS/TREES</td><td>Indicator genera: <i>Salix</i> spp., <i>Ficus</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.24</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.12</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.38</td></tr>
<tr><td>Max</td><td>250</td><td>0.59</td></tr>
</table>


</td><td>Dry duration: Safsaf willows release seeds at the end of the wet season, which are dispersed onto the wetbank. A longer dry season gives new seedlings a better chance to establish before the winter floods (Reinecke 2013).</td></tr>
<tr><td>Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0</td></tr>
<tr><td>Min Base</td><td>25</td><td>0</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.01</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.47</td></tr>
<tr><td>Max</td><td>250</td><td>-0.98</td></tr>
</table>


</td><td>Wet max 5-day Q: Increased water initially brings sustenance for growth, flowering and seed set during the wet season (Coates Palgrave 1977). Large floods scour canopies breaking off stem fragments that are dispersed downstream, which take root when deposited onto alluvial sand and grow into new trees (Reinecke 2013).</td></tr>
</table>

<table>
<tr><th>WETBANK SHRUBS/TREES</th><th>Indicator genera: <i>Salix</i> spp., <i>Ficus</i> spp.</th></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Clay and silt [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Clay and silt: Increased nutrient enriched sediments that are deposited on the wetbank as the flood recede will provide better growing conditions.</td></tr>
<tr><td>
<table>
<tr><th colspan="3">Bank erosion [All seasons]</th></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Bank erosion: Safsaf willows grow on the wetbank where they access water easily and all year round, and where they get inundated during the wet season (Reinecke 2013). Increased bank erosion will reduce and disturb habitat for growth and recruitment.</td></tr>
<tr><td colspan="2">COATES PALGRAVE K (1977) Trees of Southern Africa. C. Struik Publishers, Cape Town.
REINECKE MK (2013) Links between lateral riparian vegetation zones and flow. Unpublished PhD thesis, University of Stellenbosch, Stellenbosch, South Africa.</td></tr>
</table>

3.5.8 Reeds dry dormant

Common reed (*Phragmites australis*) is a highly productive rhizomatous perennial grass that occurs on lower lying rivers, and in freshwater and brackish wetlands (Table 3.32). It is known for its efficient sexual and reproductive strategies that allow it to spread forming dense monotypic stands (Naidoo 2020):

Habitat:	Common reed grows on the wetbank but tends to occur lower down river where there is more sand and slower flowing water (CABI 2023b). It is more tolerant of flooding (Naidoo 2020) and grows out into the open water a bit more than does Reed grass (*Phragmites mauritianus)*.
Growth:	Common reed grows in damp ground and also in standing water up to 1 m deep, or as a floating mat, tolerates brackish water, estuaries and marshes, can grow invasively, grows in all soil types as long as there is adequate moisture, protects soil from flooding and filters water (PlantZAfrica 2023). Common reed grows poorly in nutrient poor water often suffering dieback (CABI 2023b). Common reed starts growing in Spring, and dies back in Autumn, being dormant in winter (GLANSIS 2023).
Dispersal:	Common reed flowers from December to June, spreads fast by rhizome and stolon growth (5 m per year) and can form dense stands of 1 km^2 (PlantZAfrica 2023). Seed dispersal is efficient because of hair-like plumes that encourage wind dispersal, but seeds are also dispersed by water along rivers. Dispersal occurs most successfully via seed but rhizome

fragments may also take root if broken from the plant and deposited onto an alluvial bar (Juneau and Tarasoff 2013).

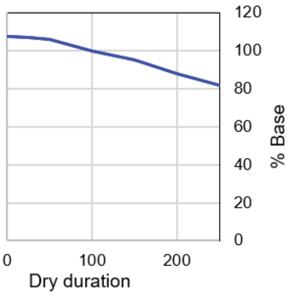
Links: Dry duration; Wet max 5-day Q; Bank erosion; Clay and silt.

Table 3.32 Reeds dry dormant links, explanations and supporting literature

REEDS DRY DORMANT	Indicator species: *Phragmites australis* (Common reed)
Link and response curve	**Explanation and supporting literature**

Dry duration [D season]

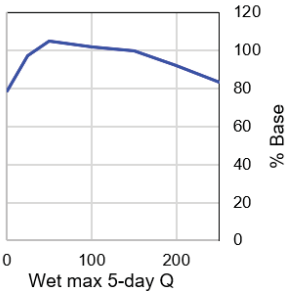
	%Base	Y1
Min	0	0.45
Min Base	25	0.41
	50	0.24
Median	100	0
	150	-0.27
Max Base	200	-0.69
Max	250	-1.05



Dry duration: Common reed starts growing in Spring, and dies back in Autumn, being dormant in winter (GLANSIS 2023). A longer dry season means a shorter growing season.

Wet max 5-day Q [F season]

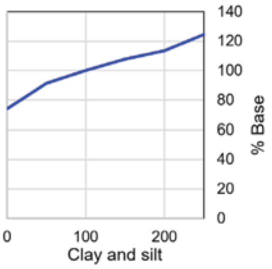
	%Base	Y1
Min	0	-1.23
Min Base	25	-0.15
	50	0.2
Median	100	0.07
	150	-0.01
Max Base	200	-0.47
Max	250	-0.98



Wet max 5-day Q: Common reed starts growing in Spring, at the start of the wet season (GLANSIS 2023). More water initially stimulates growth and flowering to a point, after which smaller plants may be uprooted and broken apart.

Clay and silt [All seasons]

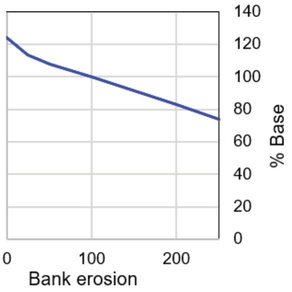
	%Base	Y1
Min	0	-1.5
Min Base	25	-1
	50	-0.5
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1.5



Clay and silt: Common reed grows poorly in nutrient poor water often suffering dieback (CABI 2023b). More nutrients rich sediments boost growth and reproduction.

Bank erosion [All seasons]

	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.5
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-1.5



Bank erosion: Common reed grows on the wetbank lower down river where there is more sand and slower flowing water (CABI 2023b). Bank erosion disturbs and reduces the wetbank habitat reducing opportunities for growth and spread.

CABI (2023b) Commonwealth Agricultural Bureaux International, *Phragmites australis* (Common reed), https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.40514, downloaded 27 April 2023.

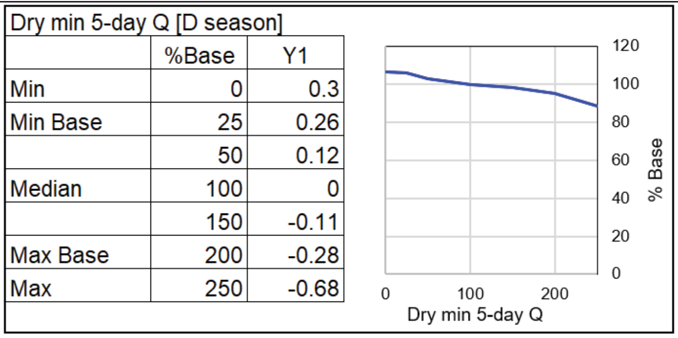
GLANSIS (2023) Great Lakes Aquatic Nonindigenous Species Information System, *Phragmites australis, https://nas.er.usgs.gov/queries/greatlakes/FactSheet.aspx?Species_ID=2937,* downloaded 27 April 2023.

3.5.9 Floating exotics

Floating exotic plants grow on the water's surface with roots that hang into the water. Relevant life history characteristics of water hyacinth are described as an example to represent this guild. Water hyacinth, *Pontederia*[1] *crassipes,* is a free floating aquatic perennial plant native to South America (Table 3.33):

Habitat:	The plant is kept afloat by its air-filled stems that are stabilised by long feathery roots (Bromilow 2010).
Growth:	Water hyacinth is one of the fastest growing plants making runners that break off to form new daughter plants (Bromilow 2010). Under favourable conditions, the area of the mats of hyacinth can double every 5 to 15 days, which represents an average increase in biomass of 12% per day (Alsgterhag and Petersson 2004). The plants grow well in still water and proliferate in response to an increase in nutrients (Howard 2005). The leaves are killed by frost and growth is impeded ≤12°C or ≥34°C, with the ideal temperature for growth = 25-30°C. But other than extreme temperatures, there are no seasonal restrictions to growth and reproduction, and the plant is able to respond to favourable conditions rapidly at any time of the year. Its pH tolerance is from 5.0-7.5 and it does not survive in salinities >5 g/litre (Wikipedia 2023c).
Dispersal:	The plant can become anchored in shallow water and reproduces sexually via purple flowers when anchored and disperses seed that remain dormant for 28 years (Sullivan and Wood 2012).
Links:	Dry min 5-day Q; Wet max 5-day Q; Backwaters and secondary channels; Clay and silt.

Table 3.33 Floating exotics links, explanations and supporting literature

<table>
<tr><td>FLOATING EXOTICS</td><td>Indicator genus: <i>Pontederia</i> spp</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>0.3</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.26</td></tr>
<tr><td></td><td>50</td><td>0.12</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.11</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.28</td></tr>
<tr><td>Max</td><td>250</td><td>-0.68</td></tr>
</table>
</td><td>Dry min 5-day Q: Floating exotics form mats (Howard 2005) that get broken apart and moved downstream with high discharge. The dry season has lower DRIFT scores than the wet season because scores are relative to the median discharge for each season.</td></tr>
</table>

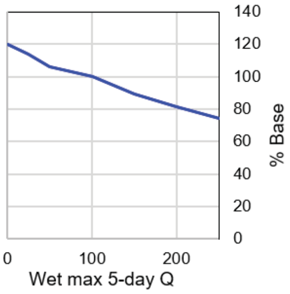
---

[1] Used to be *Eichornnia*

FLOATING EXOTICS	Indicator genus: *Pontederia* spp

Wet max 5-day Q [F season]

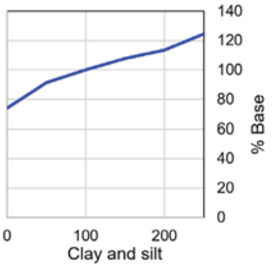
	%Base	Y1
Min	0	1.34
Min Base	25	1.01
	50	0.3
Median	100	0
	150	-0.6
Max Base	200	-1.06
Max	250	-1.47



Wet max 5-day Q: Floating aquatics form mats (Howard 2005) that get broken apart and moved downstream at high velocity. The wet season has higher DRIFT scores than the dry season because scores are relative to the median velocity for each season.

Clay and silt [All seasons]

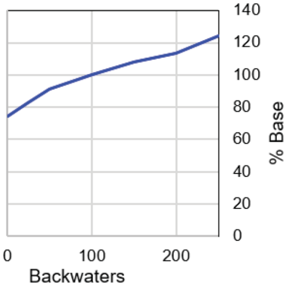
	%Base	Y1
Min	0	-1.5
Min Base	25	-1
	50	-0.5
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1.5



Clay and silt: The plants flourish in response to an increase in nutrients (Howard 2005). More FPOM means more nutrients are available for growth.

Backwaters and secondary channels [All seasons]

	%Base	Y1
Min	0	-1.5
Min Base	25	-1
	50	-0.5
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1.5



Backwaters and secondary channels: Floating aquatics grow well in the slow flowing backwaters and secondary channels at any time of the year. The plants don't perish when stranded but rather take root as a drought avoidance strategy (Venter *et al.* 2017) to float again when inundated.

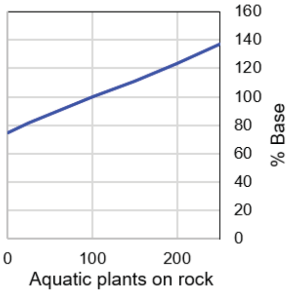
HOWARD G (2005) Invasions by plants in the inland waters and wetlands of Africa. Presentation given at the International Workshop on Biological Invasions of Inland Waters, Florence, Italy.

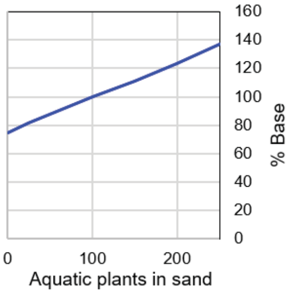
VENTER N, COWIE BW, WITKOWSKI ET, SNOW GC and BYXRNE MJ (2017) The amphibious invader: Rooted water hyacinth's morphological and physiological strategy to survive stranding and drought events. *Aquatic botany* **143** 41-48.

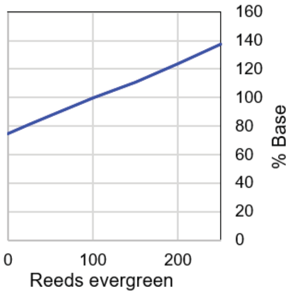
3.5.10 Agg: Aquatic veg

This indicator is a combination of aquatic vegetation growing in the channel (Table 3.34). They provide important refugia for invertebrates and juvenile fish and also then act as feeding grounds for other larger predatory invertebrates and fish.

Table 3.34 Aggregate indicator Aquatic vegetation links, explanations and supporting literature

<table>
<tr><td>Agg: AQUATIC VEG</td><td>Combined indicator: Aquatic plants on Rock, Aquatic plants in Sand</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Aquatic plants on rock [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Aquatic plants on Rock (if relevant): Straight-line relationship with Aquatic plants on Rock.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Aquatic plants in sand [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


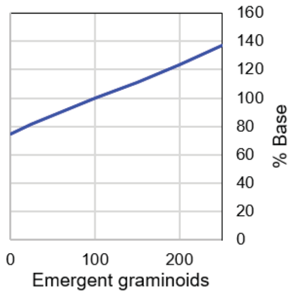
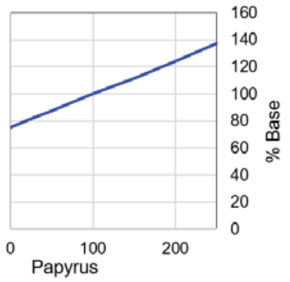
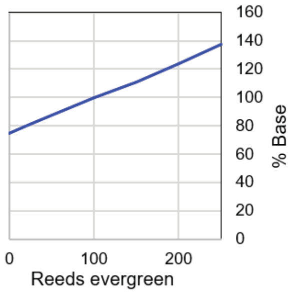
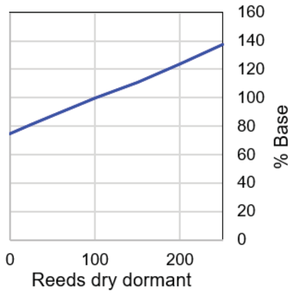
</td><td>Aquatic plants in Sand (if relevant): Straight-line relationship with Aquatic plants in Sand.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Reeds evergreen [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


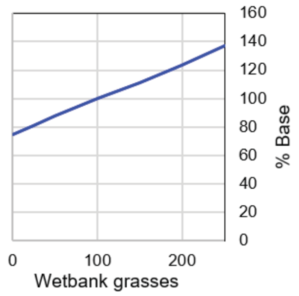
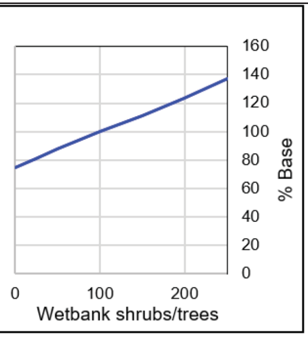
</td><td>Reeds evergreen (if relevant): Straight-line relationship with Reeds evergreen.</td></tr>
<tr><td colspan="2">Combination indicator. References for component indicators are provided on the relevant links pages.</td></tr>
</table>

3.5.11 Agg: Marginal and riparian veg

This indicator is a combination of marginal and wet bank vegetation indicators which grow where their roots are permanently inundated or where the plant is inundated at least once a year (Table 3.35). They stabilize the riverbanks, provide habitat for invertebrates and fish, and shade and resources for other animals and humans.

Table 3.35 Aggregate indicator Marginal vegetation links, explanations and supporting literature

<table>
<tr><td>Agg: MARGINAL and RIPARIAN VEG</td><td>Combined indicator: Emergent graminoids, Emergent papyrus, Reeds evergreen, Reeds dry dormant, Wetbank grasses, Wetbank shrubs/trees.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Emergent graminoids [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Emergent graminoids (if relevant): Straight-line relationship with Emergent graminoids.</td></tr>
<tr><td>Papyrus [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Papyrus (if relevant): Straight-line relationship with Papyrus.</td></tr>
<tr><td>Reeds evergreen [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Reeds evergreen (if relevant): Straight-line relationship with Reeds evergreen.</td></tr>
<tr><td>Reeds dry dormant [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Reeds dry dormant (if relevant): Straight-line relationship with Reeds dry dormant.</td></tr>
</table>

<table>
<tr><td>Agg: MARGINAL and RIPARIAN VEG</td><td>Combined indicator: Emergent graminoids, Emergent papyrus, Reeds evergreen, Reeds dry dormant, Wetbank grasses, Wetbank shrubs/trees.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Wetbank grasses [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Wetbank grasses (if relevant): Straight-line relationship with Wet grasses.</td></tr>
<tr><td>Wetbank shrubs/trees [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Wetbank shrubs/trees (if relevant): Straight-line relationship with Wet shrubs/trees.</td></tr>
</table>

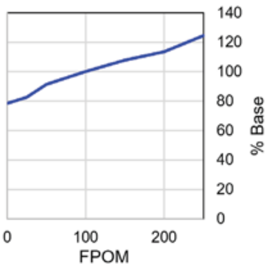
3.6 Macroinvertebrates

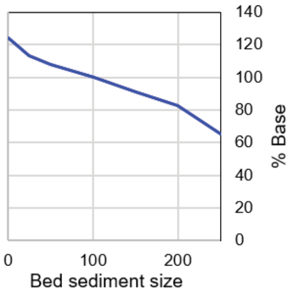
3.6.1 Caenidae

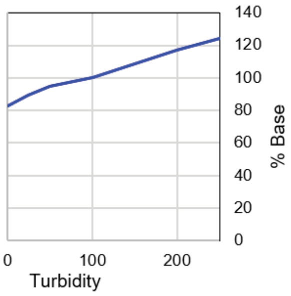
Caenidae (small square gilled mayfly; Order: Ephemeroptera) are common in silty areas and slow pools as they have gill covers that prevent suffocation during burrowing (Table 3.36). This adaptation allows them to breathe, feed and breed in fine sediments (Gerber and Gabriel 2002; Ractliffe and Dallas 2005). Some species, such as those that inhabit semi-arid and arid streams, can tolerate harsh climatic conditions (Corbin and Goonan 2010):

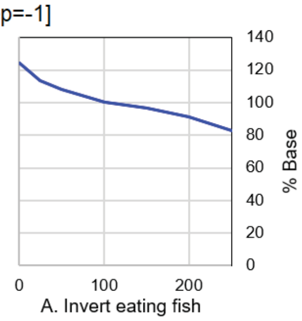
Habitat:	Slow-moving and often partially cover themselves in sediment. They are known to tolerate turbidity levels as high as 2700 NTU (Corbin and Goonan 2010). Can occur in a wide range of flows.
Food:	Filter or collect and gather tiny bits of food or scrape algae and biofilm from rocks and other substrates in their habitat (www.macroinvertebrates.org/taxa-info/ephemeroptera-larva/heptageniidae).
Emergence:	Caenids can be uni- or bivoltine, and have been reported to have quite flexible lifecycles, including aseasonal multi-voltine strategies (Perán *et al.* 1999). Typically, they emerge either at dawn or dusk, and emergence seems to be controlled by light intensity (Sartori and Brittain 2003). Adults are short-lived.
Links:	Clay and silt; Bed sediment size; Turbidity; Agg: Invertebrate-eating fish.

Table 3.36 Caenidae links, explanations and supporting literature

<table>
<tr><td>CAENIDAE</td><td>Family common name: small square gill mayflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
FPOM [All seasons]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.25</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>FPOM: Caenids feed on fine particulate organic matter.</td></tr>
<tr><td>
Bed sediment size [All seasons]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Bed sediment size: Caenids are adapted to breathe, feed and breed in fine sediments (Gerber and Gabriel 2002; Ractliffe and Dallas 2005). This allows them to out-compete other invertebrates in silty rivers.</td></tr>
<tr><td>
Turbidity [All seasons]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.6</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.2</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Turbidity: Caenids are known to tolerate turbidity levels as high as 2700 NTU (Corbin and Goonan 2010).</td></tr>
<tr><td>
A. Invert eating fish [All seasons, Step=-1]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>


</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
</table>

CORBIN TA and GOONAN P (2010) Habitat and Water Quality Preferences of Mayflies and Stoneflies from South Australian Streams. *Transactions of the Royal Society of South Australia* **134** (1) 5-18. DOI:10.1080/3721426.2010.10887129.

DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.

ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. *African Zoology* **21** (3) 257-263.

GERBER A and GABRIEL MJM (2002) Aquatic invertebrates of South African rivers. A field guide. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

<table>
<tr><td>CAENIDAE</td><td>Family common name: small square gill mayflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td colspan="2">RACTLIFFE G and DALLAS H (2005) Specialist Report: Macroinvertebrates. In: <i>Riverine RDM Report</i>. Volume 1: Specialist Reference Report. Olifants Doring Catchment Ecological Water Requirements Study. BIRKHEAD A, BOUCHER C, BROWN C, DOLLAR E, HARDING W, KAMISH W, PAXTON B, PEMBERTON C, RACTLIFFE S (eds). Unpublished DWAF Report. Project No: 2002-376. 308 pp.</td></tr>
</table>

3.6.2 *Heptageniidae*

Heptageniidae (flat headed mayfly; Order: Ephemeroptera*)* have a wide preference in flows. In southern Africa, Heptageniidae are represented by Afronurus and Comsoneuriella (Afrotropics) which show a preference for moderate to fast flow (0.3-0.6 m/s) and they favour cobbles (Thirion 2016). (Table 3.37):

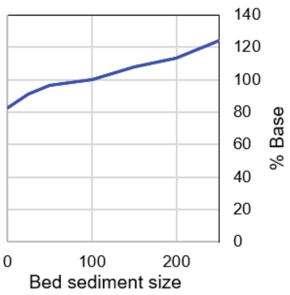
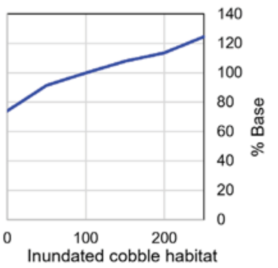
Habitat: Preference for the loose cobbles (Thirion 2007), and fast flows.

Food: Scrape algae and periphyton from rocks and other substrates. Also collector-gatherers of fine organic particles and leaves (www.macroinvertebrates.org/taxa-info/ephemeroptera-larva/heptageniidae).

Emergence: Heptageniidae are multivoltine, asynchronous, have overlapping generations and continuous emergence. Hence emergence occurs throughout the year (Sivaruban *et al.* 2010). *Neoperla* spp. lay approximately between 50-300 eggs per egg mass (Vaught 1972).

Links: Bed sediment size; Inundated cobble habitat; Algal biofilms; Filamentous algae; Agg: Invertebrate-eating fish.

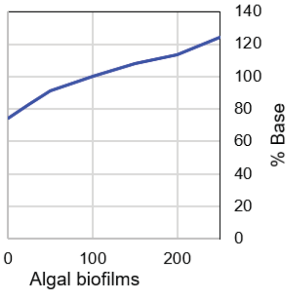
Table 3.37 Heptageniidae links, explanations and supporting literature

<table>
<tr><td>HEPTAGENIIDAE</td><td>Family common name: mayflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Bed sediment size [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Bed sediment size: Preference for the cobble biotopes (Thirion 2007). Fine sediment (≤sand) is a stressor for macroinvertebrate assemblages (Braccia and Vochell 2006) as it changes substrate composition and had direct negative effects including abrasion, clogging of filtration mechanisms, and smothering (USEPA 2003).</td></tr>
<tr><td>Inundated cobble habitat [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Inundated cobble habitat: In southern Africa, Heptageniidae are represented by Afronurus and Comsoneuriella (Afrotropics) favour cobbles (Thirion 2016).</td></tr>
</table>

HEPTAGENIIDAE	Family common name: mayflies
Link and response curve	**Explanation and supporting literature**

Algal biofilms [All seasons]

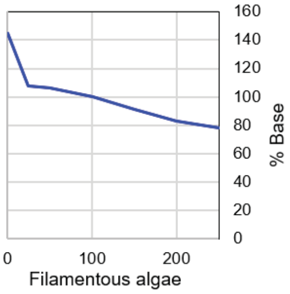
	%Base	Y1
Min	0	-1.5
Min Base	25	-1
	50	-0.5
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1.5



Algal biofilms: Benthic algae are an important component of the diet of scrapers (e.g. Mayer and Likens 1987; Eckert 2020).

Filamentous algae [All seasons]

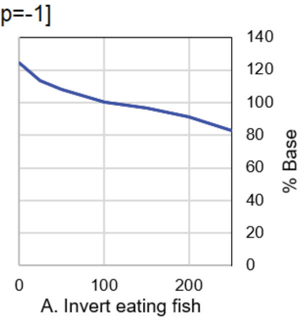
	%Base	Y1
Min	0	2
Min Base	25	0.5
	50	0.25
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-1.25



Filamentous algae: An increase in the amount of filamentous algae will have a negative impact on the abundance of Heptageniidae as it decreases the quality of cobbles available.

A. Invert eating fish [All seasons, Step=-1]

	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.5
Median	100	0
	150	-0.2
Max Base	200	-0.5
Max	250	-1



Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.

BRACCIA A and VOSHELL JR (2006) Benthic Macroinvertebrate Responses to Increasing Levels of Cattle Grazing in Blue Ridge Mountain Streams, Virginia, USA. *Environ. Monit. Assess* **131** 185-200.

DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.

ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. *African Zoology* **21** (3) 257-263.

ECKERT RA (2020) Leaf-associated periphyton in heterotrophic streams: Effect on macroinvertebrate assemblages and growth. PhD Thesis. University of Maryland, USA. 217 pp.

MAYER M and LIKENS G (1987) The Importance of algae in a shaded headwater stream as food for an abundant caddisfly (Trichoptera). *Freshwater Science* **6** (4) 262-269.

THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.

THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.

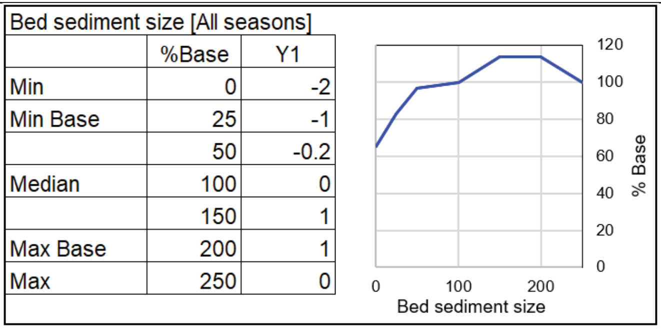
USEPA (2003) The biological effects of Suspended and Bedded Sediment (SABS) in aquatic systems: A Review Internal Report; United States Environmental Protection Agency.

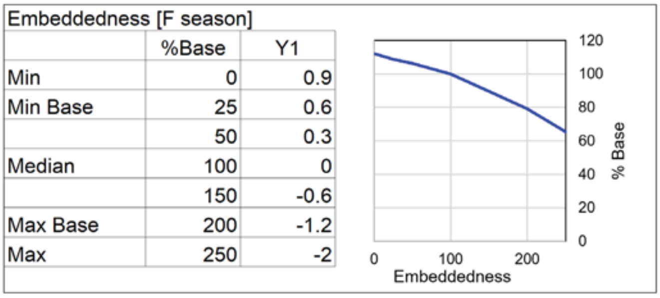
3.6.3 *Oligoneuriidae*

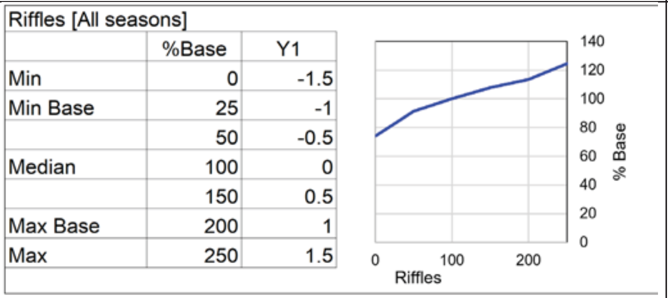
Oligoneuriidae (brush-legged mayflies; Order: Ephemeroptera) are indicators of fast flow (broken water) over cobbles and boulders (Table 3.38) mainly at high elevations (Barber-James and Lugo-Ortiz 2003):

Habitat:	They favour very fast flow (> 0.6 m/s) with cobble substrates typical of riffles or rapids (Thirion 2016).
Food:	Fine particulate matter organic (FPOM). Feeds using hairs on the foreleg to catch FPOM (www.macroinvertebrates.org/taxa-info/ephemeroptera-larva/heptageniidae).
Emergence:	Oligoneurids are univoltine with growth and development over the summer and emergence in autumn (Bouhala *et al.* 2020).
Links:	Bed sediment size; Embeddedness; Riffles; Agg: Invertebrate eating fish

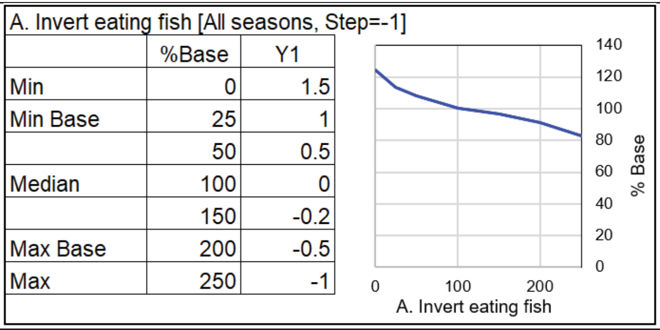
Table 3.38 Oligoneuriidae links, explanations and supporting literature

<table>
<tr><td>OLIGONEURIDAE</td><td>Family common name: brush-legged mayflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>


<table>
<tr><td colspan="3">Bed sediment size [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>0</td></tr>
</table>
</td><td>Bed sediment size: Oligoneuriidae favour larger sediment sizes, such as cobbles and boulders over fine material and bedrock.</td></tr>
<tr><td>


<table>
<tr><td colspan="3">Embeddedness [F season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>0.9</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.6</td></tr>
<tr><td></td><td>50</td><td>0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.2</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>
</td><td>Embeddedness: Oligoneurids have a preference for cobbles (particularly the undersides) which suggests that embeddedness and loss of interstitial habitat would affect this indicator.</td></tr>
<tr><td>


<table>
<tr><td colspan="3">Riffles [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Riffles: Oligoneuriidae are indicators of fast flow (broken water) over cobbles and boulders mainly at high elevations (Barber-James and Lugo-Ortiz 2003).</td></tr>
</table>

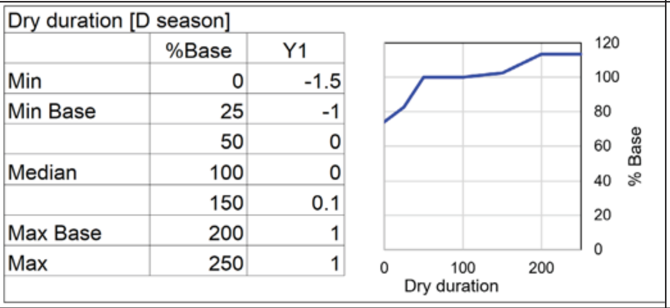
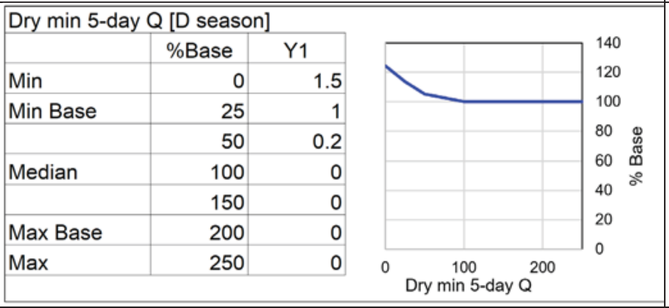
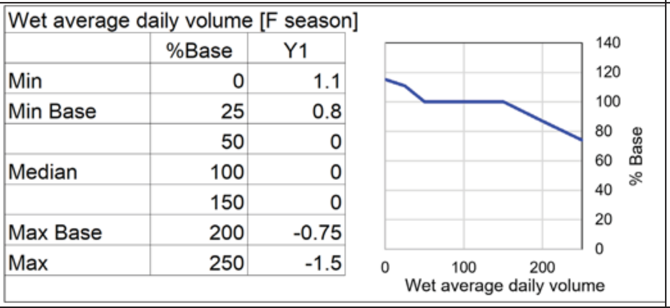
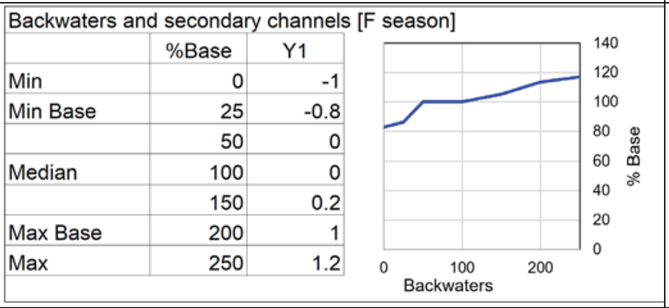
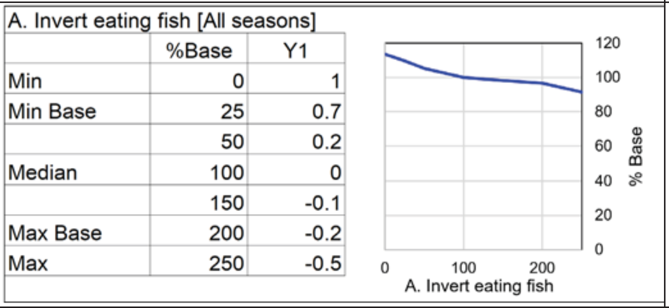
<table>
<tr><td>OLIGONEURIDAE</td><td>Family common name: brush-legged mayflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
A. Invert eating fish [All seasons, Step=-1]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>
</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008 a&b; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
<tr><td colspan="2">BARBER-JAMES HM and LUGO-ORTIZ CR (2003) Ephemeroptera. In: de Moor IJ, Day JA and DE Moor FC (ed.). <i>Guides to the Freshwater Invertebrates of Southern Africa</i>. Volume 7: Insecta I. Ephemeroptera, Odonata and Plecoptera. WRC report No TT 207/03: 16-142. Water Research Commission, Pretoria.
DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.
DE VILLIERS P and ELLENDER B (2008b) Status of the Orange-Vaal largemouth yellowfish, Labeobarbus kimberleyensis (Gilchrist and Thompson 1913). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. 92-102 pp.
ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. <i>African Zoology</i> 21 (3) 257-263.</td></tr>
</table>

3.6.4 Ceratopogonidae

Ceratopogonidae (biting midges; Order: Diptera, Table 3.39) represent a major nuisance in some countries as females of most species feed on the blood of vertebrates and can act as disease vectors:

Habitat:	Larvae occur in mud, debris, rotting vegetation or floating algal masses, rock pools, water filled holes and containers and in slow flowing areas of streams.
Food:	Larvae feed on plant and soil detritus, fungi, algae or small invertebrates. Both adult males and females feed on nectar, and most females also feed on the blood of vertebrates.
Emergence:	Adult females lay their eggs in the water or on the margins of water. Several generations per year and adults may be found during all seasons (bivoltinism).
Links:	Dry duration; Dry min 5-day Q; Wet average daily volume; Backwaters and secondary channels; Agg: Invertebrate eating fish.

Table 3.39 Ceratopogonidae links, explanations and supporting literature

<table>
<tr><td>CERATOPOGONIDAE</td><td>Family common name: biting midges</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>
</td><td>Dry duration: Ceratopogonids occupy silt and sand and are susceptible to flooding but would proliferate under low flow conditions, provided the habitat remains wetted.</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0</td></tr>
<tr><td>Max</td><td>250</td><td>0</td></tr>
</table>
</td><td>Dry min 5-day Q: Ceratopogonids would tolerate low flow (and no flow conditions) and may even increase slightly at the expense of other more sensitive taxa.</td></tr>
<tr><td>
Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.8</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.75</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>
</td><td>Wet average daily volume: Ceratopogonids would increase in abundance with zero wet season discharge to flush them out as they flourish in low flow conditions. However, any discharge larger than the median would reduce their abundance from baseline.</td></tr>
<tr><td>
Backwaters and secondary channels [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.8</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.2</td></tr>
</table>
</td><td>Backwaters and secondary channels: Ceratopogonids prefer slow moving backwaters but can be found in flowing (run) habitats (moderate flow), usually where cobbles are embedded as they favour the soft sediments. Therefore, a loss of slow to moderately flowing habitats would result in a reduction in the abundance of this taxon.</td></tr>
<tr><td>
A. Invert eating fish [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.7</td></tr>
<tr><td></td><td>50</td><td>0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.2</td></tr>
<tr><td>Max</td><td>250</td><td>-0.5</td></tr>
</table>
</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008a; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
<tr><td colspan="2">DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.</td></tr>
</table>

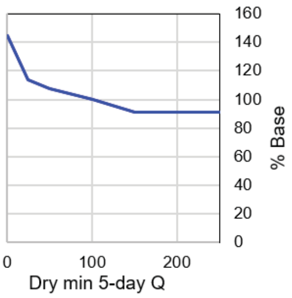
CERATOPOGONIDAE	Family common name: biting midges
Link and response curve	**Explanation and supporting literature**
ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. *African Zoology* **21** (3) 257-263.	

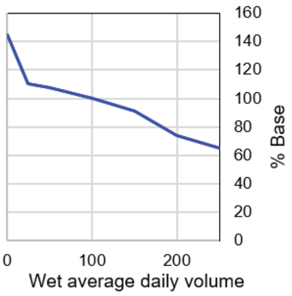
3.6.5 Chironomidae

Chironomidae (non-biting midges; Order: Diptera) are often the most abundant benthic organism and occur in all types of habitats, including rivers, streams, lakes, ponds, water supplies, and sewage systems (Table 3.40):

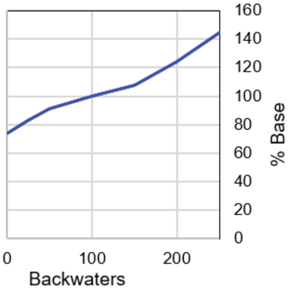
Habitat:	Chironomidae species can be collected in the whole range of habitats from the most pristine environments to the most polluted. Proliferate under reduced flow and elevated algal biomass. Chironomid larvae live at the bottom on submersed plants and other objects.
Food:	Chironomid larvae filter algae, decaying matter and other small soil organisms. Adults feed on organic debris. Some chironomids are predators.
Emergence:	In temperate regions Chironomidae are uni- or bivoltine but can have three or four annual generations.
Links:	Dry min 5-day Q; Wet average daily volume; Backwaters and secondary channels; Filamentous algae; Agg: Aquatic veg; Agg: Invertebrate eating fish.

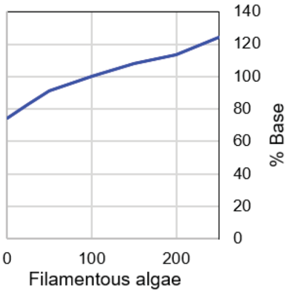
Table 3.40 Chironomidae links, explanations and supporting literature

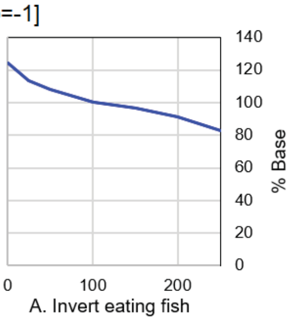
<table>
<tr><td>CHIRONOMIDAE</td><td>Family common name: non-biting midges</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-0.5</td></tr>
</table>


</td><td>Dry min 5-day Q: Chironomids would proliferate under low flow conditions as they are able to withstand stress (increase in temperatures and a range of velocities). They would proliferate in pools under these conditions.</td></tr>
<tr><td>
Wet average daily volume [F season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.75</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.5</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Wet average daily volume: Chironomids would increase in abundance with zero wet season discharge to flush them out as they flourish in low flow conditions. However, any discharge larger than the median would reduce their abundance from baseline.</td></tr>
</table>

<table>
<tr><td>CHIRONOMIDAE</td><td>Family common name: non-biting midges</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Backwaters and secondary channels [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.5</td></tr>
<tr><td>Max</td><td>250</td><td>2</td></tr>
</table>


</td><td>Backwaters and secondary channels: An increase in the area of backwaters and secondary channels would favour the proliferation of hardy taxa like chironomids.</td></tr>
<tr><td>Filamentous algae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Filamentous algae: An increase in the amount of algae favours families such as Chironomidae, Hydropsychidae, and Simulidae (Peipoch and Valett 2019).</td></tr>
<tr><td>A. Invert eating fish [All seasons, Step=-1]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>


</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008a; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
<tr><td colspan="2">DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.
ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. <i>African Zoology</i> 21 (3) 257-263.
PEIPOCH M and VALETT H (2019) Trophic interactions among algal blooms, macroinvertebrates, and brown trout: Implications for trout recovery in a restored river. <i>River Research and Application</i> 35 (9) 1563-1574.</td></tr>
</table>

3.6.6 Simuliidae

Simuliidae (black flies) occur in fast flowing rivers with firm substrata (Table 3.41).

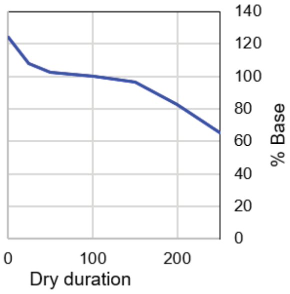
Habitat: Although Simuliidae occur over a wide range of depths, velocity and substratum types, they generally prefer shallow (10-30 cm) very fast (>0.6 m/s) water over cobbles (Thirion 2016).

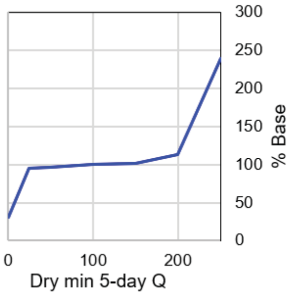
Food: Filter feeders, dependent on the concentration of food particles in the water column. Cannot survive without flowing water (>0.5 m/s) because of they feed on particles moving past in the water column (McNair *et al.* 1997).

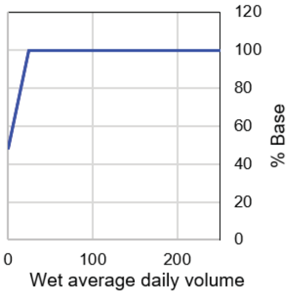
Emergence: More primitive genera are univoltine, but more advance genera, such as *Simulium* spp. are multivoltine (de Moor 1989). Emergence is adjusted to cope with a changing environment (de Moor 1989).

Links: Dry duration; Dry min 5-day Q; Wet average daily volume; Bed sediment size; FPOM; Filamentous algae.

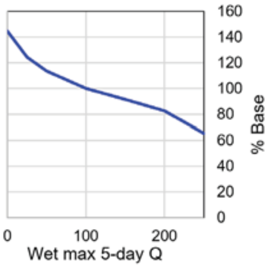
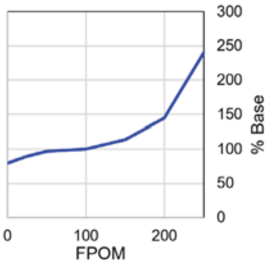
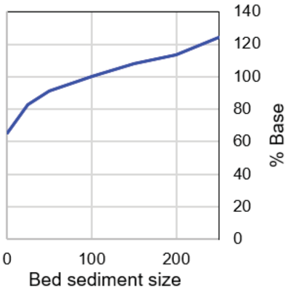
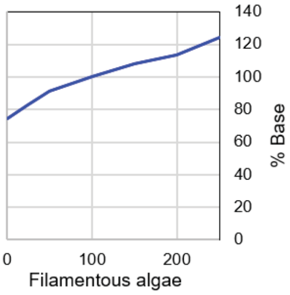
Table 3.41 Simuliidae links, explanations and supporting literature

<table>
<tr><td>SIMULIIDAE</td><td>Indicator species: <i>Simulium</i> spp. (Black Fly)</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Dry duration: The abundance of Simuliidae is likely to drop significantly as the duration of the low-flow period increases. More of the population need to overwinter as eggs as the low-flow period lengthens. A shorter low-flow period also reduces risks of mortality caused by elevated water temperatures during the low-flow period. The elimination of the low-flow period is typically what leads to outbreaks of pest blackflies in spring. With a dam in place, the response is shifted because of the increased availability of food (phytoplankton), but the shape of the response is likely to remain much the same.</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-4</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.3</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.05</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>3</td></tr>
</table>


</td><td>Dry min 5-day Q: Filter-feeding is not possible if flows stop, so flow cessation is certain to reduce populations. However, a proportion of the population is expected to be present as adults or eggs, so short periods of flow cessation will not eliminate the entire population. Most likely to become a problem at >1 m/s (Rivers-Moore and de Moor 2008). Simuliidae tend to proliferate under constant flows which can result due to elevated dry season flows.</td></tr>
<tr><td>
Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>0</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0</td></tr>
<tr><td>Max</td><td>250</td><td>0</td></tr>
</table>


</td><td>Wet average daily volume: Cannot survive without flowing water (>0.5 m/s) because they feed on particles moving past in the water column (McNair <i>et al.</i> 1997). Most likely to become a problem at >1 m/s (Rivers-Moore and de Moor 2008).</td></tr>
</table>

<table>
<tr><td>SIMULIIDAE</td><td>Indicator species: <i>Simulium</i> spp. (Black Fly)</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1.5</td></tr>
<tr><td></td><td>50</td><td>1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>

</td><td>Wet max 5-day Q: Without floods, simulids could reach pest proportions as they proliferate under constant, elevated base flows.</td></tr>
<tr><td>FPOM [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.6</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1</td></tr>
<tr><td>Max Base</td><td>200</td><td>2</td></tr>
<tr><td>Max</td><td>250</td><td>3</td></tr>
</table>

</td><td>FPOM: Filter feeders, dependent on the concentration of food particles in the water column (McNair <i>et al.</i> 1997).</td></tr>
<tr><td>Bed sediment size [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Bed sediment size: Simuliids tend to attach to large boulders and bedrock (Vazques <i>et al.</i> 2020).</td></tr>
<tr><td>Filamentous algae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Filamentous algae: An increase in the amount of algae favours families such as Chironomidae, Hydropsychidae, and Simulidae (Peipoch and Valett 2019).</td></tr>
</table>

MCNAIR JN, NEWBOLD JD and HART DD (1997) Turbulent transport of suspended particles and dispersing benthic organisms: how long to hit bottom? *Journal of Theoretical Biology* **188** (1) 29-52.

PEIPOCH M and VALETT H (2019) Trophic interactions among algal blooms, macroinvertebrates, and brown trout: Implications for trout recovery in a restored river. *River Research and Application* **35** (9) 1563-1574.

RIVERS-MOORE NA and FC DE MOOR (2008) Impact of winter flow regulation on pest-level populations of blackfly (Diptera: Simuliidae) and non-target faunal communities in a South African river. *African Journal of Aquatic Science* **33** (2) 125-134.

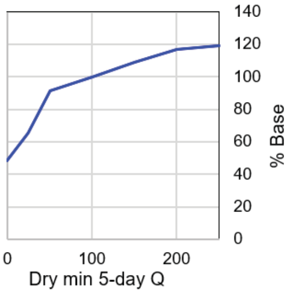
VASQUEZ D, FLOWERS RW and SPRINGER M (2009) Life history of five small minnow mayflies (Ephemeroptera: Baetidae) in a small tropical stream on the Caribbean slope of Costa Rica. *Aquatic Insects* **31** (14) 319-332.

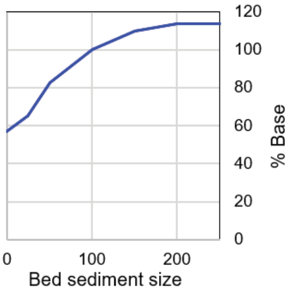
3.6.7 Elmidae

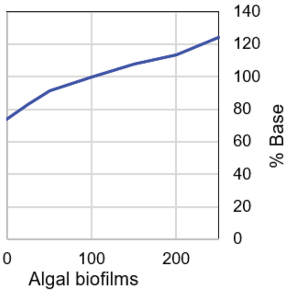
Elmidae (riffle beetles; Order: Coleoptera) are cosmopolitan freshwater coleopterans that inhabit clean and well-oxygenated running waters in their larval and adult stages (Table 3.42):

Habitat:	Elmid beetles have a strong preference for fast-flowing water (>1.0 m/s), with boulder, bedrock or woody snag substrates (Thirion 2014) but will inhabit GSM.
Food:	Collector-gatherers and scrapers that feed mainly on algae and detritus.
Emergence:	Larval and adult stages are aquatic.
Links:	Dry min 5-day Q; Bed sediment size; Algal biofilms; Filamentous algae.

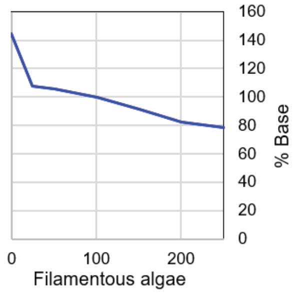
Table 3.42 Elmidae links, explanations and supporting literature

<table>
<tr><td>ELMIDAE</td><td>Family common name: riffle beetles</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Dry min 5-day Q [D season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-2</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.2</td></tr>
<tr><td>Max</td><td>250</td><td>1.3</td></tr>
</table>


</td><td>Dry min 5-day Q: A decrease in discharge will have a resultant decrease in velocities, which will have a resultant negative impact on Elmidae, which show preference for fast flowing water (Jack and Balke 2008).</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Bed sediment size [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-2</td></tr>
<tr><td></td><td>50</td><td>-1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.7</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>


</td><td>Bed sediment size: Elmidae show a strong preference for the cobble biotope (Thirion 2007, 2016) as well as some preference for GSM.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Algal biofilms [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Algal biofilms: Elmidae feed on algae and biofilms (White 2009).</td></tr>
</table>

<table>
<tr><td>ELMIDAE</td><td>Family common name: riffle beetles</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Filamentous algae [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.5</td></tr>
<tr><td></td><td>50</td><td>0.25</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.25</td></tr>
</table>


</td><td>Filamentous algae: An increase in the amount of filamentous algae will have a negative impact on the abundance of Elmidae as it decreases the quality of cobbles available.</td></tr>
<tr><td colspan="2">JÄCH MA and BALKE M (2008) Global diversity of water beetles (Coleoptera) in freshwater. <i>Hydrobiologia</i> 595 419-442.
WHITE DS (2009) Coleoptera (Beetles) in Aquatic Ecosystems, <i>Encyclopedia of Inland Waters</i>, Elsevier 144-156 pp.
THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.
THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.</td></tr>
</table>

3.6.8 Hydropsychidae

Hydropsychidae (net spinning caddisflies; Order: Trichoptera) are common in rivers and are sometimes used as an indicator of contaminants and pollutants in the water (Table 3.43):

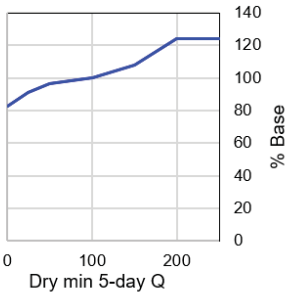
Habitat: Preference for cobble (Thirion 2007) in very fast flowing water >0.6 m^3/s (Thirion 2014). Often found in fast flowing broken water cascades such as riffles and cascades. Sensitive to siltation (Scott 1988). Often surround themselves with cases made of organic material, such as vegetation or debris, or small stones or sand grains bound together by silk.

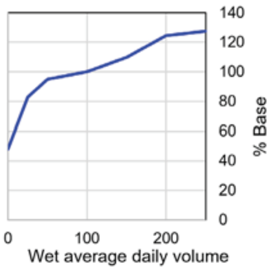
Food: Hydropsychids spin a net or sieve made of fine silk that are used to catch algae, detritus and smaller invertebrates. Different genera spin nets of different mesh sizes and shapes depending on what food type they are targeting. Because of this technique of food collection, hydropsychids require flowing water to ensnare items of food into their net.

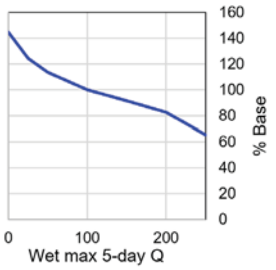
Emergence: Includes species that are univoltine (Basaguren *et al.* 2002), bi- and trivoltine (Mackay 1984). Up to 800 eggs are laid at a time (de Moor and Scott 2003).

Links: Dry min 5-day Q; Wet average daily volume; Bed sediment size; Filamentous algae; Agg: Invertebrate-eating fish.

Table 3.43 Hydropsychidae links, explanations and supporting literature

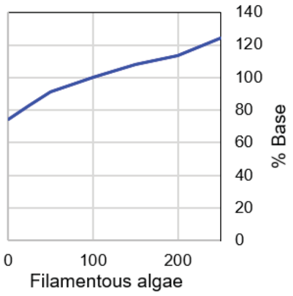
<table>
<tr><td>HYDROPSYCHIDAE</td><td>Family common name: net spinning caddisflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.5</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


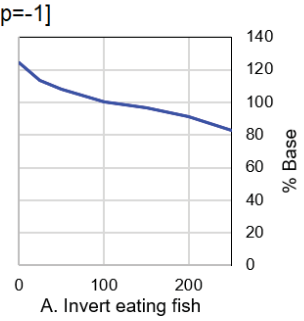
</td><td>Dry min 5-day Q: Hydropsychids spin a net or sieve made of fine silk that are used to catch algae, detritus and smaller invertebrates. Different genera spin nets of different mesh sizes and shapes depending on what food type they are targeting. Because of this technique of food collection, hydropsychids require flowing water to ensnare items of food into their net. Further as dry season flows decline, the extent of preferred fast flowing biotopes (e.g. riffles and cascades) will decrease and so will the abundance of Hydropsychidae.</td></tr>
<tr><td>
Wet average daily volume [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.3</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.7</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.5</td></tr>
<tr><td>Max</td><td>250</td><td>1.6</td></tr>
</table>


</td><td>Wet average daily volume: Less discharge will have a negative impact on Hydropsychidae which are flow sensitive (Thirion 2014). An increase in discharge will result in an increase in average and maximum velocities which will affect the Hydropsychidae positively with a resultant increase in abundance.</td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>2</td></tr>
<tr><td>Min Base</td><td>25</td><td>1.5</td></tr>
<tr><td></td><td>50</td><td>1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>


</td><td>Wet max 5-day Q: Large floods will cause disturbance to habitat and wash away Hydropsychidae. Lower flows will results in stable flows.</td></tr>
<tr><td>
Bed sediment size [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>0</td></tr>
</table>


</td><td>Bed sediment size: Preference for the cobble biotopes (Thirion 2007). Fine sediment (≤sand) is a stressor for some macroinvertebrate species (Braccia and Vochell 2006) as it changes substrate composition and had direct negative effects including abrasion, clogging of filtration mechanisms and smothering (USEPA 2003).</td></tr>
</table>

<table>
<tr><td>HYDROPSYCHIDAE</td><td>Family common name: net spinning caddisflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Filamentous algae [All seasons]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


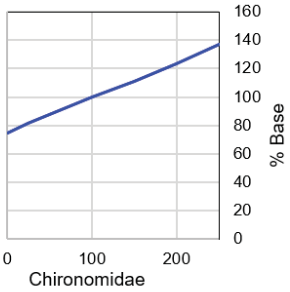
</td><td>Filamentous algae: An increase in the amount of algae favours families such as Chironomidae, Hydropsychidae, and Simulidae (Peipoch and Valett 2019).</td></tr>
<tr><td>
<table>
<tr><td colspan="3">A. Invert eating fish [All seasons, Step=-1]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>


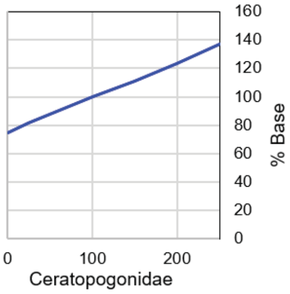
</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008 a&b; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
<tr><td colspan="2">BRACCIA A and VOSHELL JR (2006) Benthic Macroinvertebrate Responses to Increasing Levels of Cattle Grazing in Blue Ridge Mountain Streams, Virginia, USA. <i>Environ. Monit. Assess</i> 131 185-200.
DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.
DE VILLIERS P and ELLENDER B (2008b) Status of the Orange-Vaal largemouth yellowfish, Labeobarbus kimberleyensis (Gilchrist and Thompson 1913). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. 92-102 pp.
PEIPOCH M and VALETT H (2019) Trophic interactions among algal blooms, macroinvertebrates, and brown trout: Implications for trout recovery in a restored river. <i>River Research and Application</i> 35 (9) 1563-1574.
THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.
THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.
USEPA (2003) The biological effects of Suspended and Bedded Sediment (SABS) in aquatic systems: A Review Internal Report; United States Environmental Protection Agency.</td></tr>
</table>

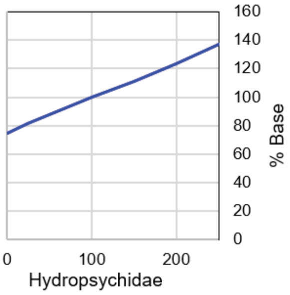
3.6.9 *Agg: Invert food for inverts*

This indicator is a combination of the outcomes for three invertebrate indicators (as relevant) and is provided for ease of reference to a food supply for invertebrate-eating invertebrates, such as Gomphidae and Palaemonidae (Table 3.44).

Table 3.44 Constituent links for aggregate indicator Invertebrate food for other invertebrates

<table>
<tr><th>Agg: INVERTEBRATE FOOD FOR OTHER INVERTEBRATES</th><th>Combined indicator: Chironomidae; Ceratopogonidae, Hydropsychidae</th></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Chironomidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Chironomidae (if relevant): Straight-line relationship with Chironomidae</td></tr>
<tr><td>
Ceratopogonidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Ceratopogonidae (if relevant): Straight-line relationship with Ceratopogonidae</td></tr>
<tr><td>
Hydropsychidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


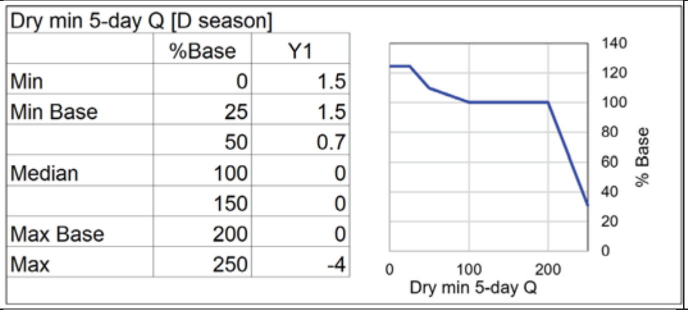
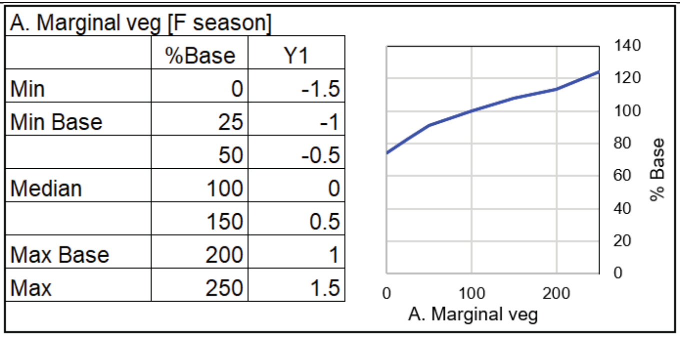
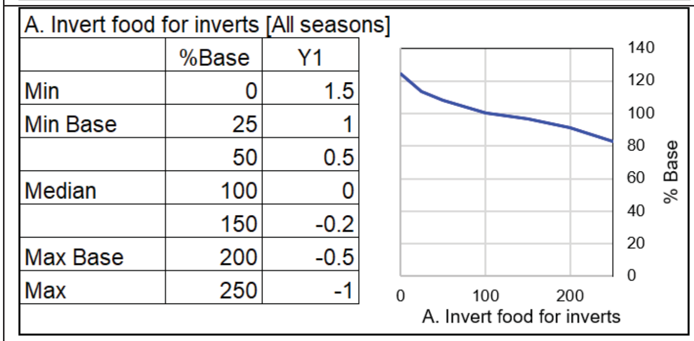
</td><td>Hydropsychidae (if relevant): Straight-line relationship with Hydropsychidae</td></tr>
<tr><td colspan="2">Combination indicator. References for component indicators are provided on the relevant links pages.</td></tr>
</table>

3.6.10 Coenagrionidae

Although Coenagrionidae (narrow-winged damselflies; Order: Odonata) prefer lentic water some species are found in rivers (Table 3.45):

Habitat:	Inhabit marginal vegetation and prefer slower flowing waters, i.e. 0.1-0.3 m/s.
Food:	Coenagrionidae are predators and eat mainly small invertebrates.
Emergence:	Most Coenagrionidae are univoltine, few bivoltine, others multivoltine (Phiri *et al.* 2012).
Links:	Dry min 5-day Q; Agg: Marginal and riparian veg; Agg: Inver food for inverts.

Table 3.45 Coenagrionidae links, explanations and supporting literature

<table>
<tr><td>COENAGRIONIDAE</td><td>Family common name: narrow-winged damselflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1.5</td></tr>
<tr><td></td><td>50</td><td>0.7</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>0</td></tr>
<tr><td>Max</td><td>250</td><td>-4</td></tr>
</table>
</td><td>Dry min 5-day Q: Coenagrionidae prefer slow velocities (0.1-0.3 m/s) (Thirion 2007, 2014). Wetted perimeter, depth and velocities decrease as discharge decreases. This means that there is less volume of water available. Unseasonal elevated flows in the dry season impact negatively on Coenagrionidae (Dickens <i>et al.</i> 2008).</td></tr>
<tr><td>
A. Marginal veg [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>
</td><td>Agg: Marginal and riparian veg: Coenagrionids show a specific preference for marginal vegetation (Gerber and Gabriel 2002; Ractliffe and Dallas 2005).</td></tr>
<tr><td>
A. Invert food for inverts [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>
</td><td>Agg: Invert food for inverts: Coenagrionidae are predators and eat mainly small invertebrates.</td></tr>
</table>

DICKENS C, GRAHAM M, DE WINNAAR G, HODGSON K, TIBA F, SEKWELE R, SIKHAKHANE S, DE MOOR F, BARBER-JAMES H and VAN NIEKERK K (2008) The impacts of high winter flow releases from an impoundment on in-stream ecological processes. Report to the Water Research Commission. WRC Report No 1307/1/08. ISBN 978-1-77005-691-6. 187 pp.

GERBER A and GABRIEL MJM (2002) Aquatic invertebrates of South African rivers. A field guide. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

RACTLIFFE G and DALLAS H (2005) Specialist Report: Macroinvertebrates. In: *Riverine RDM Report*. Volume 1: Specialist Reference Report. Olifants Doring Catchment Ecological Water Requirements Study. BIRKHEAD A, BOUCHER C, BROWN C, DOLLAR E, HARDING W, KAMISH W, PAXTON B, PEMBERTON C, RACTLIFFE S (eds). Unpublished DWAF Report. Project No: 2002-376. 308 pp.

THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.

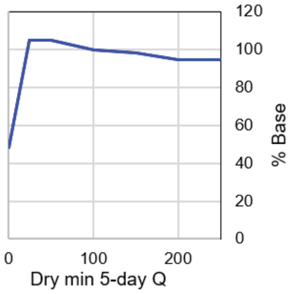
THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.

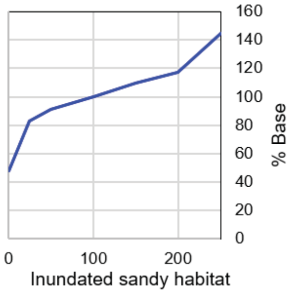
3.6.11 *Gomphidae*

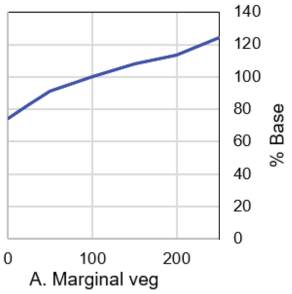
Gomphidae (club tailed dragonflies or club tails, Order: Odonata) are common inhabitants of rivers where there is soft sediment (Table 3.46). The nymphs propel themselves through the water with a miniature jet engine, taking water in below their mouths and shooting it out their back ends:

Habitat:	Burrow in sand and mud; particle size 0.6-1 mm (Huggins and DuBois 1982), with velocities between 0.1-0.3 m/s (Ractliffe 2009).
Food:	Feed on a wide variety of aquatic insects, such as midges, bugs and beetles; as well as small fish, shrimp and tadpoles.
Emergence:	Semivoltine, i.e. generation time is greater than one year (Burcher and Smock 2002). Gomphidae are year-round residents that are non-dispersing (UNDP-GEF 2013).
Links:	Dry 5-day min Q; Bed sediment size; Inundated sandy habitat; Agg: Marginal and riparian veg; Agg: Invert food for inverts.

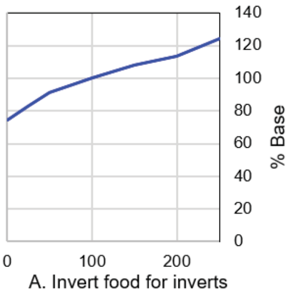
Table 3.46 Gomphidae links, explanations and supporting literature

<table>
<tr><td>GOMPHIDAE</td><td>Family common name: dragonflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>0.2</td></tr>
<tr><td></td><td>50</td><td>0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.3</td></tr>
<tr><td>Max</td><td>250</td><td>-0.3</td></tr>
</table>


</td><td>Dry min 5-day Q: Gomphidae are year-round residents that are non-dispersing (UNDP-GEF 2013). Literature shows them to be semivoltine – i.e. generation time is greater than one year (Burcher and Smock 2002). With increased discharge, less amounts of slow velocities are available for Gomphidae.</td></tr>
<tr><td>
Inundated sandy habitat [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-3</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.7</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.2</td></tr>
<tr><td>Max</td><td>250</td><td>2</td></tr>
</table>


</td><td>Inundated sandy habitat: Gomphidae larvae can be found burrowing in the substrate made of sand or silt, (Novelo-Gutiérrez <i>et al.</i> 2018). As the amount of sand increases, so will the number of gomphids.</td></tr>
<tr><td>
A. Marginal veg [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Agg: Marginal and riparian veg: Mature Gomphidae perch on the ground or on vegetation to thermoregulate and watch for prey or potential mates (Remsburg 2011).</td></tr>
</table>

<table>
<tr><td>GOMPHIDAE</td><td>Family common name: dragonflies</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
A. Invert food for inverts [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


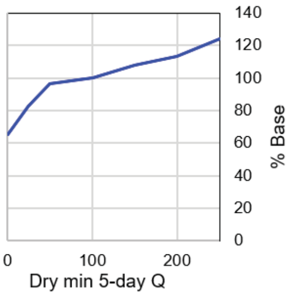
</td><td>Agg: Invert food for inverts: The nymph feed on a wide variety of aquatic insects, including mosquito larvae, aquatic fly larvae, mayfly larvae, and freshwater shrimp. The adults are also carnivorous.</td></tr>
<tr><td colspan="2">UNDP-GEF ORANGE-SENQU STRATEGIC ACTION PROGRAMME (2013) EFR Monitoring Programme. Research Project on Environmental Flow Requirements of the Fish River and the Orange-Senqu River Mouth.
BURCHER CL and SMOCK LA (2002) Habitat distribution, dietary composition and life history characteristics of odonate nymphs in a blackwater coastal plain stream. <i>American Midland Naturalist</i> 148 75-89.
NOVELO-GUTIÉRREZ R, RAMÍREZ A and GONZÁLEZ-SORIANO E (2018) Superfamily Gomphoidea. In <i>Thorp and Covich's Freshwater Invertebrates</i>. Academic Press. 377-397 pp
REMSBURG A (2011) Relative influence of prior life stages and habitat variables on dragonfly (Odonata: Gomphidae) densities among lake sites. <i>Diversity</i> 3 (2) 200-216.</td></tr>
</table>

3.6.12 Perlidae

Perlidae (stone flies; Order: Plecoptera) occur in in fast flowing mountain and coastal rivers (Table 3.47). Stoneflies require unpolluted, swift flowing water with high oxygen content, and so they are often used as an indicator of the relative water quality of a river (Hilsenhoff 2001).

Habitat:	Sides and undersides of stream-bottom structures, such as boulders, stones and plant detritus.
Food:	Caddisflies, midges, and other small invertebrates.
Emergence:	Univoltine, with emergence in spring.
Links:	Dry min 5-day Q; Wet average daily volume; Bed sediment size; Filamentous algae; A. Food for inverts; A. invertebrate eating fish

Table 3.47 Perlidae links, explanations and supporting literature

<table>
<tr><td>PERLIDAE</td><td>Indicator genus: <i>Neoperla</i> spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


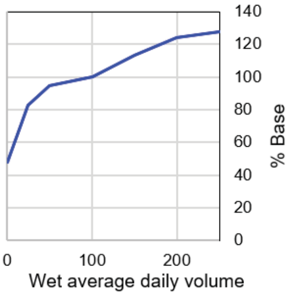
</td><td>Dry min 5-day Q: Less discharge will have a negative impact on Perlidae which are flow sensitive (Thirion 2014). An increase in discharge will result in an increase in average and maximum velocities which will affect the Perlidae positively with a resultant increase in abundance.</td></tr>
</table>

PERLIDAE | Indicator genus: *Neoperla* spp.

Link and response curve | **Explanation and supporting literature**

Wet average daily volume [F season]

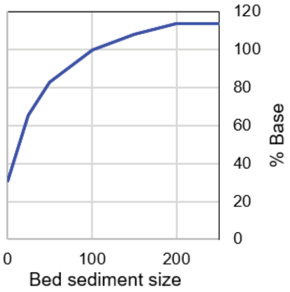
	%Base	Y1
Min	0	-3
Min Base	25	-1
	50	-0.3
Median	100	0
	150	1
Max Base	200	1.5
Max	250	1.6



Wet average daily volume: Less discharge will have a negative impact on Perlidae which are flow sensitive (Thirion 2014). An increase in discharge will result in an increase in average and maximum velocities which will affect the Perlidae positively with a resultant increase in abundance.

Bed sediment size [All seasons]

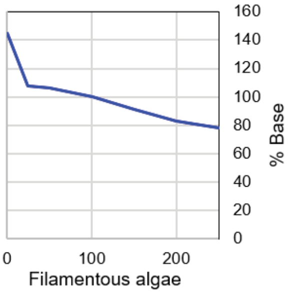
	%Base	Y1
Min	0	-4
Min Base	25	-2
	50	-1
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1



Bed sediment size: Preference for the boulder and cobble biotopes (Thirion 2007). Fine sediment (≤sand) is a stressor for may invertebrate species (Braccia and Vochell 2006) as it changes substrate composition and had direct negative effects including abrasion, clogging of filtration mechanisms and smothering (USEPA 2003).

Filamentous algae [All seasons]

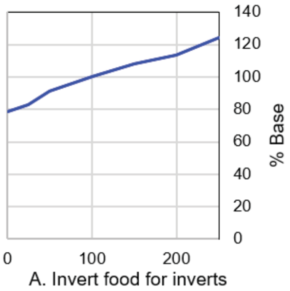
	%Base	Y1
Min	0	2
Min Base	25	0.5
	50	0.25
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-1.25



Filamentous algae: An increase in the amount of filamentous algae will have a negative impact on the abundance of Perlidae as it decreases the quality of cobbles available.

A. Invert food for inverts [All seasons]

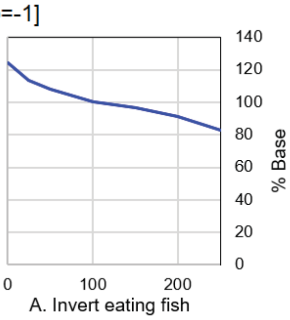
	%Base	Y1
Min	0	-1.25
Min Base	25	-1
	50	-0.5
Median	100	0
	150	0.5
Max Base	200	1
Max	250	1.5



Agg: Invert food for inverts: Perlidae eat caddisflies, midges, and other small invertebrates (Macroinvertebrate.org 2023).

A. Invert eating fish [All seasons, Step=-1]

	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.5
Median	100	0
	150	-0.2
Max Base	200	-0.5
Max	250	-1



Agg: Fish abundance: Fish eat aquatic invertebrates (De Villiers and Ellender 2008 a&b; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.

BRACCIA A and VOSHELL JR (2006) Benthic Macroinvertebrate Responses to Increasing Levels of Cattle Grazing in Blue Ridge Mountain Streams, Virginia, USA. *Environ. Monit. Assess* **131** 185-200.

<table>
<tr><td>PERLIDAE</td><td>Indicator genus: Neoperla spp.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td colspan="2">DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.
DE VILLIERS P and ELLENDER B (2008b) Status of the Orange-Vaal largemouth yellowfish, Labeobarbus kimberleyensis (Gilchrist and Thompson 1913). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. 92-102 pp.
THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.
THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.
USEPA (2003) The biological effects of Suspended and Bedded Sediment (SABS) in aquatic systems: A Review Internal Report; United States Environmental Protection Agency.
MACROINVERTEBRATES.ORG (2023) Available at https://www.macroinvertebrates.org/taxa-info/plecoptera-larva/perlidae Accessed on 5 May 2023.</td></tr>
</table>

3.6.13 *Freshwater snails*

Freshwater snails are gastropod molluscs and occur in quiet waters (Table 3.48)[2]:

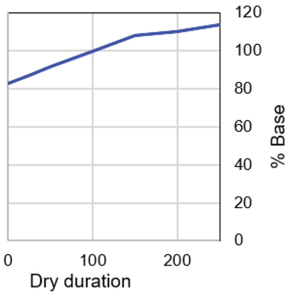
Habitat: Various, but often found in quite areas with plentiful vegetation.

Food: Snails are omnivores but eat mostly small plants and scrape algae and fine detritus from submerged rocks, wood and macrophytes.

Breeding: Freshwater snails usually produce several generations per year. Snails are hermaphroditic, i.e. both male and female organs and can produce fertilized eggs by themselves[3].

Links: Dry duration; Wet max 5-day Q; A. Aquatic veg; A. Marginal veg; A. Snail eating fish.

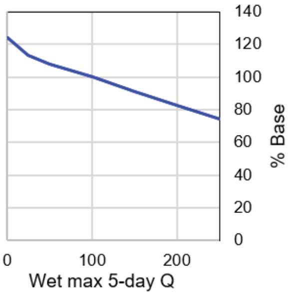
Table 3.48 Freshwater snails links, explanations and supporting literature

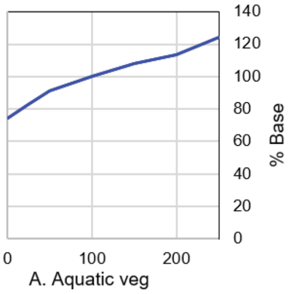
<table>
<tr><td>FRESHWATER SNAILS</td><td>Indicator species: Bulinus globosus</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Dry duration [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.75</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.75</td></tr>
<tr><td>Max</td><td>250</td><td>1</td></tr>
</table>

</td><td>Dry duration: Gastropods flourish in slow or no flow conditions and therefore, an extended dry season would result in the proliferation of gastropods.</td></tr>
</table>

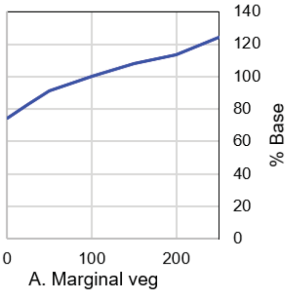
---

[2] Other mollusca such as bivalves occur in SADC rivers but snails are considered most relevant because they are a host for some vector borne diseases, such as Schistosomiasis.

[3] https://animals.mom.com/life-cycle-of-the-freshwater-snail-7771162.html.

<table>
<tr><td>FRESHWATER SNAILS</td><td>Indicator species: <i>Bulinus globosus</i></td></tr>
<tr><td>
Wet max 5-day Q [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1</td></tr>
<tr><td>Max</td><td>250</td><td>-1.5</td></tr>
</table>


</td><td>Wet max 5-day Q: Snails that may proliferate in the absence of flood disturbance. Snails are sensitive to increased velocities and several studies have shown natural flooding to significantly reduce snail abundance (Woolhouse and Chandiwana 1990; cited in Quayle <i>et al.</i> 2010). Fritsch (1993; cited in Quayle <i>et al.</i> 2010) demonstrated that flushing of a river in Tanzania was effective in removing <i>Bulinus globosus</i> almost entirely (cited in Quayle <i>et al.</i> 2010).</td></tr>
<tr><td>
A. Aquatic veg [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Agg: Aquatic veg: Increased leaf surfaces among floating and submerged macrophytes allow grazing on periphyton while also creating protective cover from many kinds of predators (Covich 2010).</td></tr>
<tr><td>
A. Marginal veg [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Agg: Marginal and riparian veg: Freshwater snails attach to submerged and emergent vegetation (Appleton 1977; Hart 1979).</td></tr>
<tr><td colspan="2">APPLETON CC (1977) The influence of temperature on the life-cycle and distribution of Biomphalaria pfeifferi (Krauss, 1948) in South-Eastern Africa. <i>International journal for parasitology</i> 7 (5) 335-345.
COVICH AP (2010) Winning the biodiversity arms race among freshwater gastropods: competition and coexistence through shell variability and predator avoidance. <i>Hydrobiologia</i> 653 (1) 191-215.
HART RC (1979) <i>The invertebrate communities: zooplankton, zoobenthos and littoral fauna</i> (Vol. 36). W. Junk, Hague. 108-161 pp.
QUAYLE LM, APPLETON CC and DICKENS CWS (2010) The effects of stream flow manipulation on the invertebrate hosts of malaria, bilharzia and liver fluke disease. Report to the Water Research Commission by Institute of Natural Resources WRC Report No. TT 456/10.
SKELTON P (1995) <i>A Complete Guide to the Freshwater Fishes of Southern Africa</i>. Southern Book Publishers, 1993. ISBN 1-86812-350-2.</td></tr>
</table>

3.6.14 Atyidae

Atyid freshwater shrimps are globally distributed and form an important part of freshwater ecosystems, particularly in the tropics and subtropics (Table 3.49).

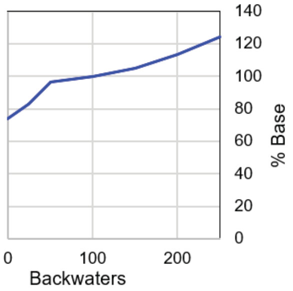
Habitat: Atyidae are vegetation dwellers and prefer slow flowing water, i.e. 0.1-0.3 m/s, with a moderate to high sensitivity to changes in water quality.

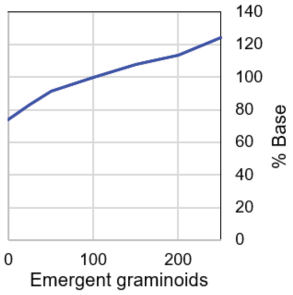
Food: Generally, atyid shrimp are collectors feeding on plant and animal detritus or bacteria or algal particles. Most species feed by gathering food particles off rocks and plants using the brush-like setae on the tips of the claws of their first and second legs.

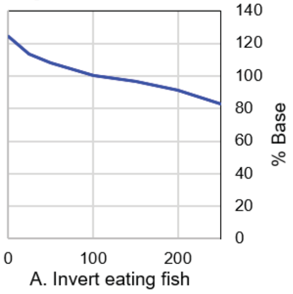
Breeding: Reproduction occurs during the summer months, though some species reproduce year-round. They exhibit one of two life history traits: amphidromy, in which planktonic larvae develop in the sea; and landlocked, in which lecithotrophic larvae develop in freshwater.

Links: Backwaters and secondary channels; Marginal graminoids; A. Invert eating fish

Table 3.49 Atyidae links, explanations and supporting literature

<table>
<tr><td colspan="2">ATYIDAE</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Backwaters and secondary channels [F season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Backwaters and secondary channels: Shrimps (Atyidae) require still backwater pools for breeding and feeding. Atyidae can proliferation in slow flowing or still waters (<0.1 m/s) (Thirion 2016) with a sandy substrate and leaf litter (Yam and Dudgeon 2005). Thus, an increase in the extent of this habitat during the dry season will favour proliferation of shrimp.</td></tr>
<tr><td>
Emergent graminoids [All seasons]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>


</td><td>Emergent graminoids: Shrimps are obligate vegetation dwellers and thus the quality and quantity of marginal vegetation is important for this group (Thirion 2007). A diversity of leaf types promotes habitat heterogeneity and food quality with an impact on shrimp abundance.</td></tr>
<tr><td>
A. Invert eating fish [All seasons, Step=-1]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>


</td><td>Agg: Fish abundance: Fish eat aquatic invertebrates (e.g. De Villiers and Ellender 2008 a; Eccles 1986), the more invertebrate-eating fish, the greater the predation on invertebrates.</td></tr>
<tr><td colspan="2">
THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.
THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.
YAM RS and DUDGEON D (2005) Stable isotope investigation of food use by Caridina spp.(Decapoda: Atyidae) in Hong Kong streams. <i>Journal of the North American Benthological Society</i> 24 (1) 68-81.
DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in
</td></tr>
</table>

<table>
<tr><td colspan="2">ATYIDAE</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td colspan="2">South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.
ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. <i>African Zoology</i> 21 (3) 257-263.</td></tr>
</table>

3.6.15 Palaemonidae

Palaemonidae (freshwater prawns) are amphidromous, nocturnal, sluggish in nature and territorial (Ling 1969):

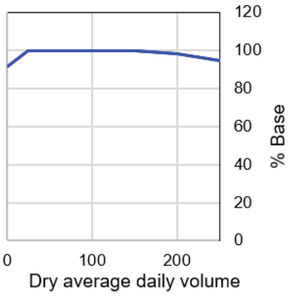
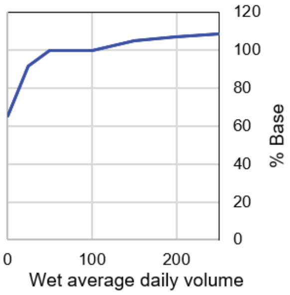
Habitat: *M. rosenbergii* is bottom dwelling with a preference for sandy or muddy sediments. During the day they remain half buried in sediments and prefer shallow, detritus rich and vegetated areas.

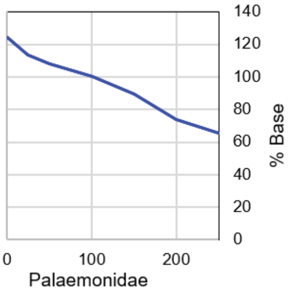
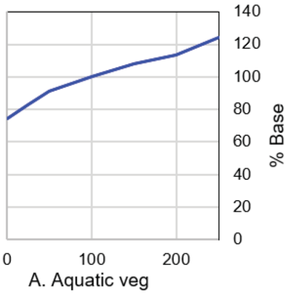
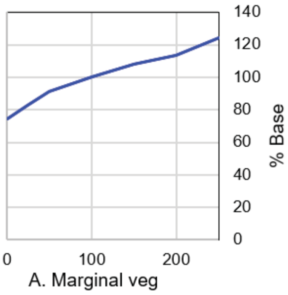
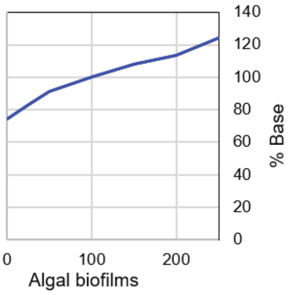
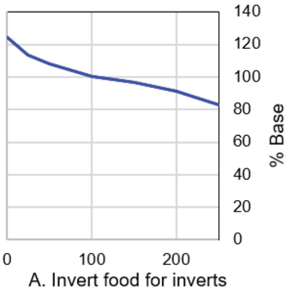
Food: Omnivorous benthivores. Feed mainly on algae, aquatic plants, molluscs, oligochaetes, aquatic insects, and other crustaceans.

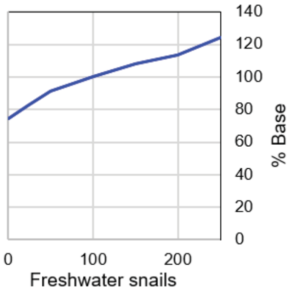
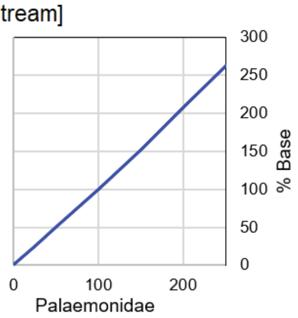
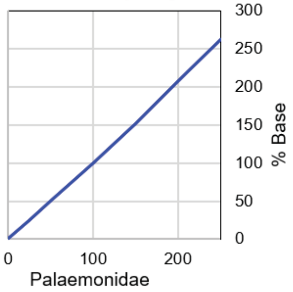
Breeding: Migration by females from the river to the estuary during high flows, larval development in brackish water and up river migration by juveniles during low flows.

Links: Dry average daily volume; Wet average daily volume; Bed sediment size; Algal biofilms; A. Aquatic veg; A. Marginal veg, A. Food for inverts, Freshwater snails, Palaemonidae (migration links) (Table 3.50).

Table 3.50 Palaemonidae links, explanations and supporting literature

<table>
<tr><td>PALAEMONIDAE</td><td>Indicator species: <i>Macrobrachium rosenbergii</i></td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Dry average daily volume [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-0.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>0</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.1</td></tr>
<tr><td>Max</td><td>250</td><td>-0.3</td></tr>
</table>

</td><td>Dry average daily volume: Elevated runoff or no runoff in the dry season negatively impacts on breeding success for freshwater prawns, as the larvae are unable to migrate upstream (Collocott <i>et al.</i> 2014).</td></tr>
<tr><td>Wet average daily volume [F season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.5</td></tr>
<tr><td></td><td>50</td><td>0</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.4</td></tr>
<tr><td>Max</td><td>250</td><td>0.6</td></tr>
</table>

</td><td>Wet average daily volume: Higher flows during the wet season months benefit the Palaemonidae in terms of their movement downstream to brackish waters to reproduce (Collocott <i>et al.</i> 2014).</td></tr>
</table>

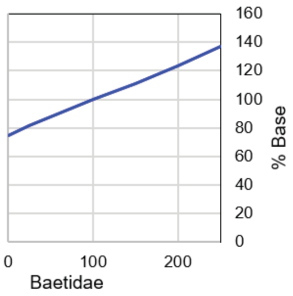
<table>
<tr><td>PALAEMONIDAE</td><td>Indicator species: <i>Macrobrachium rosenbergii</i></td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Bed sediment size [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>-1.5</td></tr>
<tr><td>Max</td><td>250</td><td>-2</td></tr>
</table>

</td><td>Bed sediment size: <i>M. rosenbergii</i> is bottom dwelling with a preference for sandy or muddy sediments.</td></tr>
<tr><td>A. Aquatic veg [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Agg: Aquatic veg: Submerged macrophyte beds provide the prawns with refuge against predation (Walsh and Mitchell 1998; Froneman 2006) and food.</td></tr>
<tr><td>A. Marginal veg [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Agg: Marginal and riparian veg: Submerged vegetation on the river edges provide the prawns with refuge against predation (Walsh and Mitchell 1998; Froneman 2006).</td></tr>
<tr><td>Algal biofilms [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Algal biofilms: Algae including biofilms are a food source for Palaemonidae (Burns and Walker 2000).</td></tr>
<tr><td>A. Invert food for inverts [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>1</td></tr>
<tr><td></td><td>50</td><td>0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>-0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>-0.5</td></tr>
<tr><td>Max</td><td>250</td><td>-1</td></tr>
</table>

</td><td>Agg: Invert food for inverts: Prawns are omnivorous benthivores (e.g. Budeba and Cowx 2007). Feed mainly on algae, aquatic plants, molluscs, oligochaetes, aquatic insects and other crustaceans.</td></tr>
</table>

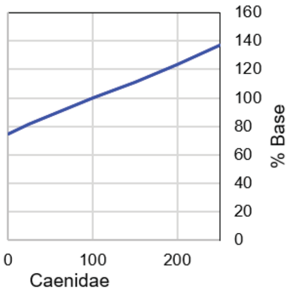
<table>
<tr><td>PALAEMONIDAE</td><td>Indicator species: <i>Macrobrachium rosenbergii</i></td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Freshwater snails [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>1</td></tr>
<tr><td>Max</td><td>250</td><td>1.5</td></tr>
</table>

</td><td>Freshwater snails: Prawns are omnivorous benthivores (e.g. Budeba and Cowx 2007). Feed mainly on algae, aquatic plants, molluscs, oligochaetes, aquatic insects and other crustaceans.</td></tr>
<tr><td>Palaemonidae [All seasons, Site=upstream]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-5.751</td></tr>
<tr><td>Min Base</td><td>25</td><td>-4.342</td></tr>
<tr><td></td><td>50</td><td>-2.895</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>2.119</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.762</td></tr>
<tr><td>Max</td><td>250</td><td>3.138</td></tr>
</table>

</td><td>Palaemonidae (MIGRATION LINK from upstream): Female freshwater prawns migrate from river sites to the estuary (Ling 1969). This link is for the downstream movement, and should link to the next upstream site. All relevant upstream sites should be linked in series.</td></tr>
<tr><td>Palaemonidae [All seasons, Site=downstream, Step=-1]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-5.751</td></tr>
<tr><td>Min Base</td><td>25</td><td>-4.342</td></tr>
<tr><td></td><td>50</td><td>-2.895</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>2.119</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.762</td></tr>
<tr><td>Max</td><td>250</td><td>3.138</td></tr>
</table>

</td><td>Palaemonidae (MIGRATION LINK from downstream): Freshwater prawn larvae migrate from estuary to the river (Ling 1969). This link if for the upstream movement, and should link to the next downstream site. All relevant downstream sites should be linked in series. Because it is upstream movement, the links must be the previous year.</td></tr>
<tr><td colspan="2">BUDEBA YL and COWX IG (2007) The role of the freshwater shrimp Caridina nilotica (Roux) in the diet of the major commercial fish species in Lake Victoria, Tanzania. <i>Aquatic Ecosystem Health and Management</i> 10 (4) 368-380. DOI:10.1080/14634980701703876.
BURNS A and WALKER KF (2000) Biofilms as food for decapods (atyidae, Palaemonidae) in the river Murray, south australia. <i>Hydrobiologia</i> 437 83-90.
COLLOCOTT SJ, Vivier L and Cyrus DP (2014) Prawn community structure in the subtropical Mfolozi-Msunduzi estuarine system, Kwazulu-Natal, South Africa. <i>African Journal of Aquatic Science</i> 39 (2) 127-140.
FRONEMAN PW (2006) The population dynamics of the caridean shrimp, Palaemon peringueyi, in a small intermittently open Eastern Cape estuary. <i>African Journal of Aquatic Science</i> 31 197-203.
LING SW (1969) The general biology and development of <i>Macrobrachium rosenbergii</i> (de Man). <i>FAO Fisheries Report</i>. 57 (3) 589-606.
WALSH CJ and MITCHELL BD (1998) Factors associated with variations in the abundance of epifaunal caridean shrimps between and within estuarine seagrass meadows. <i>Marine and Freshwater Research</i> 49 769-777.</td></tr>
</table>

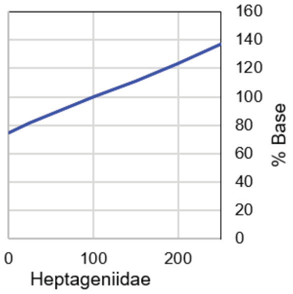
3.6.16 Agg: EPT food for fish

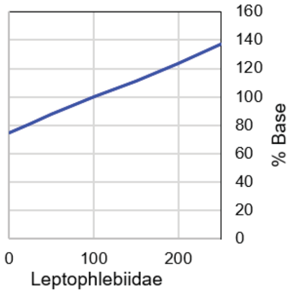
This indicator is a combination of the outcomes for three invertebrate orders and is provided for ease of reference to a food supply for invertebrate-eating fish that typically target Ephemeroptera, Plecoptera and Trichoptera or EPT (Table 3.51).

Table 3.51 Aggregate indicator EPT food for fish links, explanations and supporting literature

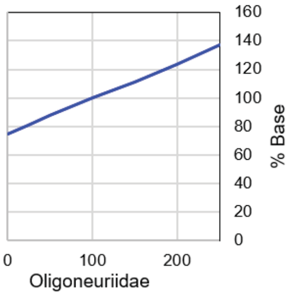
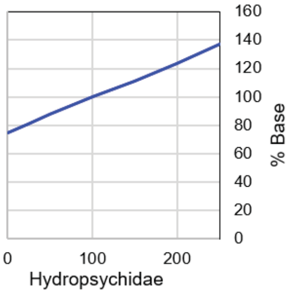
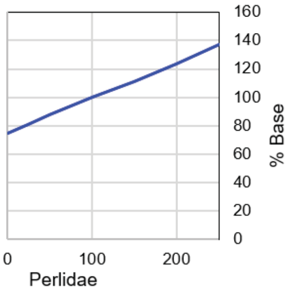
<table>
<tr><td>Agg: EPT FOOD FOR FISH</td><td>Combined indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Hydropsychidae, Perlidae</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Baetidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Baetidae (if relevant): Straight-line relationship with Baetidae.</td></tr>
<tr><td>
Caenidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Caenidae (if relevant): Straight-line relationship with Caenidae.</td></tr>
<tr><td>
Heptageniidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Heptageniidae (if relevant): Straight-line relationship with Heptageniidae.</td></tr>
<tr><td>
Leptophlebiidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


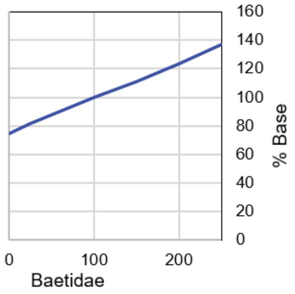
</td><td>Leptophlebiidae (if relevant): Straight-line relationship with Leptophlebiidae.</td></tr>
</table>

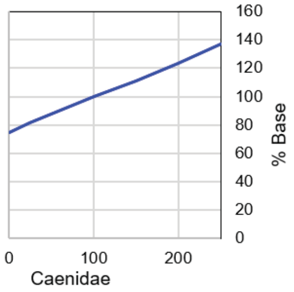
<table>
<tr><td>Agg: EPT FOOD FOR FISH</td><td>Combined indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Hydropsychidae, Perlidae</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Oligoneuriidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Oligoneuriidae (if relevant): Straight-line relationship with Oligoneuriidae.</td></tr>
<tr><td>Hydropsychidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Hydropsychidae (if relevant): Straight-line relationship with Hydropsychidae.</td></tr>
<tr><td>Perlidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Perlidae (if relevant): Straight-line relationship with Perlidae.</td></tr>
<tr><td colspan="2">Combination indicator. References for component indicators are provided on the relevant links pages.</td></tr>
</table>

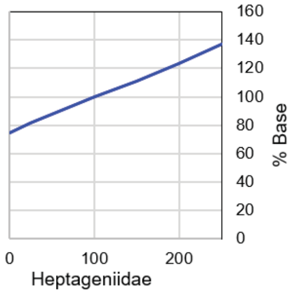
3.6.17 Agg: Invert food for fish

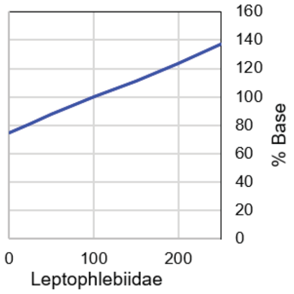
This indicator is a combination of the outcomes for several invertebrate groups and is provided for ease of reference to a food supply for fish that eat an array of macroinvertebrates (Table 3.52).

Table 3.52 Constituent links for aggregate indicator Invert food for fish

<table>
<tr><td>Agg: INVERT FOOD FOR FISH</td><td>Combined indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Ceratopogonidae; Chironomidae; Simuliidae; Hydropsychidae, Perlidae</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Baetidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Baetidae (if relevant): Straight-line relationship with Baetidae.</td></tr>
<tr><td>Caenidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Caenidae (if relevant): Straight-line relationship with Caenidae.</td></tr>
<tr><td>Heptageniidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


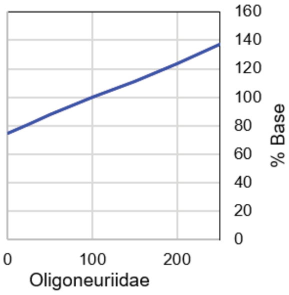
</td><td>Heptageniidae (if relevant): Straight-line relationship with Heptageniidae.</td></tr>
<tr><td>Leptophlebiidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>


</td><td>Leptophlebiidae (if relevant): Straight-line relationship with Leptophlebiidae.</td></tr>
</table>

Agg: INVERT FOOD FOR FISH	Combined indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Ceratopogonidae; Chironomidae; Simuliidae; Hydropsychidae, Perlidae
Link and response curve	**Explanation and supporting literature**

Oligoneuriidae [All seasons]

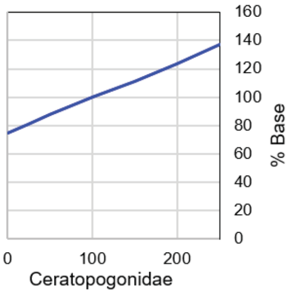
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



Oligoneuriidae (if relevant): Straight-line relationship with Oligoneuriidae.

Ceratopogonidae [All seasons]

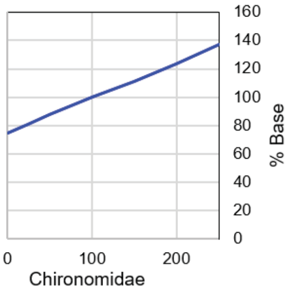
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



Ceratopogonidae (if relevant): Straight-line relationship with Ceratopogonidae.

Chironomidae [All seasons]

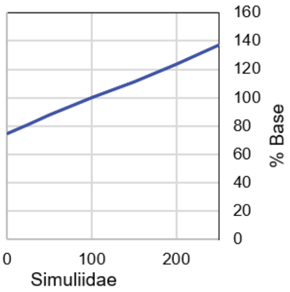
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



Chironomidae (if relevant): Straight-line relationship with Chironomidae.

Simuliidae [All seasons]

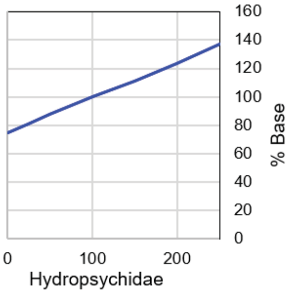
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



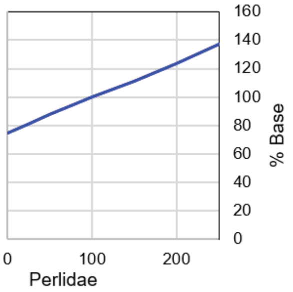
Simuliidae (if relevant): Straight-line relationship with Simuliidae.

Hydropsychidae [All seasons]

	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



Hydropsychidae (if relevant): Straight-line relationship with Hydropsychidae.

<table>
<tr><td>Agg: INVERT FOOD FOR FISH</td><td>Combined indicator: Baetidae; Caenidae; Heptageniidae; Leptophlebiidae; Oligoneuriidae; Ceratopogonidae; Chironomidae; Simuliidae; Hydropsychidae, Perlidae</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>Perlidae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Perlidae (if relevant): Straight-line relationship with Perlidae.</td></tr>
<tr><td colspan="2">Combination indicator. References for component indicators are provided on the relevant links pages.</td></tr>
</table>

3.7 Fish

A set of fish indicators (or guilds) was derived from an analysis of the 11 DRIFT databases combined with information from FishBase, SANBI and other sources. The indicators listed in Table 3.53 are based on groupings of fish species with similar hydrological, hydro/substrate or hydro/vegetation preferences. In addition to these drivers, to effectively predict how a particular fish guild would be affected by changes in the flow of water, sediment or biota, links should also be chosen from the lists provided relating to preferences for feeding habitat, food, breeding habitat, migration requirements, etc. The choices will be based on the relevant fish (one or several) used to represent the guild or indicator in the particular river / river reach. Unavoidably, there is overlap across the indicator groups, e.g. species that favour quiet vegetated waters often also make use of floodplains.

The idea, for a river reach of interest, is to

- choose a set of indicators from Table 3.53, based the habitats present and if the information is available, those species known to be present,
- for each selected indicator choose one or more fish species from the river under study to represent the indicator (or deal with the indicator guild as a whole, but this is often more difficult), and
- for each selected indicator, use the links and associated response curves provided (Table 3.54 to Table 3.59) as a starting point and, if necessary, choose alternative or additional links based on the species selected for that indicator (e.g. selecting from Table 3.61 and /or Table 3.62).
  - To expand on this, the choice of example species for each indicator will determine the links to be included. For example, the worked example for Riffle dependent fish uses *Amphilius uranoscopus* as the indicator species. These feed on invertebrates and hence are linked to invertebrates as a food source. However, if *Labeo cylindricus* is present in the river under study and is chosen as the indicator species to represent Riffle dependent fish then the food link will be replaced by Algal biofilms as these fish are algivorous.

Generally, when adding or replacing links keep in mind that in general, links should include:

- Hydrology seasonal flow patterns for habitat and breeding requirements
- Geomorphological and / or vegetation habitat for living and/or breeding: e.g. riffles, backwaters, floodplain vegetation, substrate for breeding (e.g. vegetation (bubble nests), cobble beds, sandy habitat for sand nests)
- Food: e.g. algae, vegetation, invertebrates, other fish species or a combination

Table 3.53 List of fish indicators

Generic Indicator	**Description**	**Example species**
Riffle dependent fish (small)	Fish that inhabit cobble or rocky habitat in riffles with swiftly flowing water. They may have adaptations that allow them to cling to stones.	*Amphilius uranoscopus, Chiloglanis anoterus, Chiloglanis emarginatus, Chiloglanis fasciatus, Chiloglanis paratus, Chiloglanis pretoriae, Chiloglanis swierstrai Labeo cylindricus, Labeo molybdinus, Chiloglanis neumanni, Opsaridium peringueyi, Enteromius eutaenia, Enteromius lineomaculatus.*
Quiet vegetated water fish	Fish that inhabit quiet vegetated waters in river littorals, and backwaters.	*Coptodon rendalli, Enteromius trimaculatus, Lacustricola katangae, Enteromius paludinosus, Tilapia sparrmanii, Pseudocrenilabrus philander*
Floodplain dependent fish	Fish that are dependent on access to the floodplain for key portions of their life history.	*Schilbe intermedius, Enteromius radiatus, Enteromius paludinosus, Enteromius bifrenatus, Enteromius poechii, Lacustracola species, Marcusenius altisambesi, Marcusenius macrolepidotus, Labeo lunatus.*
Migratory fish (large)	Fish that must migrate up or downstream to reach their spawning, breeding and / or nursery areas.	Obligatory*: Anguilla mossambica, Anguilla bengalensis labiata, Anguilla marmorata,.* Large bodied riffle dependent*: Labeobarbus codringtonii, Labeobarbus altianalis, Labeobarbus caudovittatus, Labeobarbus kimberlyensis, Labeobarbus marequensis.* Other*: Labeo cylindricus, Labeo molybdinus, Labeo rosae, Labeo congoro, Labeo codringtonii, Hydrocynus vittatus, Enteromius trimaculatus, Enteromius bifrenatus, Micralestes acutidens, Schilbe intermedius, Enteromius afrohamiltoni, Clarias gariepinus.*
Tolerant fish	Fish that are tolerant of a wide range of conditions and do not have specialised flow, geomorphic, or vegetation requirements.	*Clarias gariepinus, Tilapia sparrmanii, Oreochromis mossambicus*

3.7.1 Riffle dependent fish (small)

This indicator is for riffle-dependent species, primarily consisting of relatively small-bodied fish. (Larger bodied fish that utilise riffles during migration and / or for reproduction are included in the Migratory fish group (Section 3.7.4). The indicator refers to fish that prefer and inhabit cobble or rocky habitat in riffles with swiftly flowing water or require this habitat for spawning (Table 3.54). They consequently prefer Fast Shallow and Fast Deep velocity-depth habitats. They may have adaptations that allow them to cling to stones.

Examples: *Amphilius uranoscopus, Chiloglanis anoterus, Chiloglanis emarginatus, Chiloglanis fasciatus, Chiloglanis paratus, Chiloglanis pretoriae, Chiloglanis swierstrai Labeo cylindricus, Labeo molybdinus, Chiloglanis neumanni, Opsaridium peringueyi, Enteromius eutaenia, Enteromius lineomaculatus*.

Indicator spp. for worked example: *Amphilius uranoscopus* (common mountain catfish or stargazer mountain catfish) and many of the *Amphilius* genus of the family Amphiliidae (Loach catfish or African catfish) are riffle specialists. *A. uranoscopus* is widespread in central and east Africa extending from Kenya down through Tanzania and Mozambique to Kwazulu-Natal, South Africa (SANBI 2023a). It also occurs in the Okavango and Zambezi systems and has been reported in Ethiopia (Skelton 2001). They prefer cobble or rocky habitat in riffles or swiftly flowing water where they cling to stones with paired fins adapted to form suckers (Skelton 2001). They feed on stream invertebrates (Skelton 2001). They breed over an extended period in summer (Skelton 2001), laying eggs underneath stones.

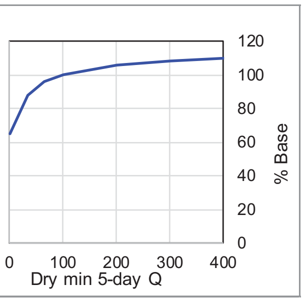
Habitat: Prefer clear, flowing, well oxygenated water in rocky habitats.

Breeding: Breed in summer and require stony habitat (FishBase 2023a).

Food: Feed on stream insects and other small organisms off rock surfaces (FishBase 2023a).

Links: Dry min 5-day Q; Wet average daily volume; Wet duration; Riffles; Embeddedness; Agg: Invert food for fish.

Table 3.54 Riffle dependent fish links, explanations and supporting literature

<table>
<tr><td>RIFFLE DEPENDENT FISH</td><td>Indicator species: <i>Amphilius uranoscopus</i></td></tr>
<tr><td>Links and response curves</td><td>Explanations and supporting literature</td></tr>
<tr><td>
Dry min 5-day Q [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.00</td></tr>
<tr><td>Min Base</td><td>35</td><td>-0.70</td></tr>
<tr><td></td><td>65</td><td>-0.20</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>200</td><td>0.30</td></tr>
<tr><td>Max Base</td><td>300</td><td>0.60</td></tr>
<tr><td>Max</td><td>400</td><td>0.70</td></tr>
</table>


</td><td>Dry min 5-day Q: Favour fast flowing, well oxygenated water (Ngugi <i>et al.</i> 2009). Depend on flowing water over rocky substrate in the dry season. May congregate in deeper areas in the dry season (Kolding and van Zwieten 2012). Lower dry season flows could have strong negative impacts on them. They may become stressed through crowding and increased exposure to predation and fishing (Kolding and van Zwieten 2012) and through restriction of movement to other areas for feeding and refuge (Baras and Lucas 2001).</td></tr>
</table>

RIFFLE DEPENDENT FISH

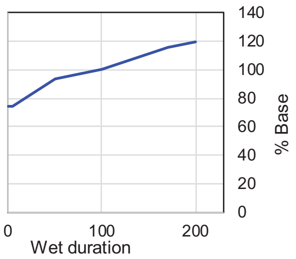
Indicator species: *Amphilius uranoscopus*

Links and response curves

Explanations and supporting literature

Wet duration [F season]

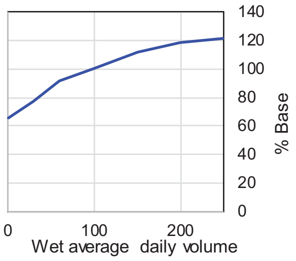
	%Base	Y1
Min	0	-1.50
Min Base	5	-1.50
	50	-0.35
Median	100	0.00
	135	0.50
Max Base	170	1.10
Max	200	1.30



Wet duration: Generally a long spawning period over the wet season (Marriott 1997; Ngugi et al 2009). Short wet seasons limit the availability of optimal habitat and reduce the spawning period and annual recruitment and increase the duration of physiological stress and competition (Welcomme 1985; Junk *et al.* 1989; Hoeinghaus *et al.* 2007). A longer wet season will benefit the population by increasing available habitat, food and spawning opportunities.

Wet average daily volume [F season]

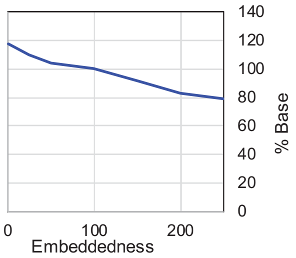
	%Base	Y1
Min	0	-2.00
Min Base	30	-1.30
	60	-0.50
Median	100	0
	150	0.85
Max Base	200	1.27
Max	250	1.40



Wet average daily vol: Adapted for fast flow and rocky habitats (Skelton 1995, Seegers 2008, Ngugi et al 2009). Reduced availability of these habitats increases physiological stress, intra- and inter-specific competition, and reduces fitness and condition. During very large floods (>1:5 years) juveniles may seek hydraulic cover in marginal areas and adults in the benthos. Feeding and spawning may be interrupted. **

Embeddedness [D season]

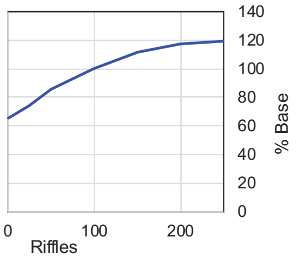
	%Base	Y1
Min	0	1.20
Min Base	25	0.70
	50	0.15
Median	100	0
	150	-0.50
Max Base	200	-1.00
Max	250	-1.20



Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered, or sunken into the silt, sand, or mud of the stream bottom. Generally, as rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning and egg incubation.

Riffles [D season]

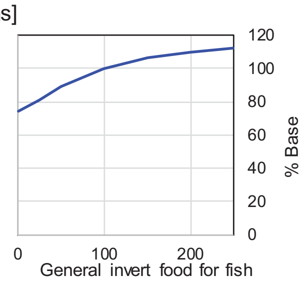
	%Base	Y1
Min	0	-2.00
Min Base	25	-1.50
	50	-0.80
Median	100	0
	150	0.90
Max Base	200	1.20
Max	250	1.30



Riffles are a source of high-quality cobble or rocky habitat and diverse fauna; therefore, an increased frequency of occurrence greatly enhances the diversity of the stream community. Riffle dependent fish are sensitive to the area of riffle habitat available at a site.

General invert food for fish [All seasons]

	%Base	Y1
Min	0	-1.50
Min Base	25	-1.10
	50	-0.65
Median	100	0
	150	0.30
Max Base	200	0.70
Max	250	0.90



Agg: Invert food for fish: Reduced prey abundance will negatively impact growth, development and survival (Marriott 1997, Ngugi *et al.* 2009).

Add or replace substrate / breeding links based on species, if required

See Section 3.7.7 for alternative habitats

RIFFLE DEPENDENT FISH	Indicator species: *Amphilius uranoscopus*
Links and response curves	**Explanations and supporting literature**
Add or replace food links based on species, if required	See Section 3.7.7 for alternative foods, e.g. grazers like *Labeo cylindricus* would link to Algal biofilms instead.

BARAS E and LUCAS MC (2001) Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *International Journal of Ecohydrology & Hydrobiology* **1** (3) 291-304.

FISHBASE (2023a) Available at: https://www.fishbase.se/summary/9419 [Accessed June 1, 2023]

HOEINGHAUS DJ, WINEMILLER KO and BIRNBAUM JS (2007) Local and regional determinants of stream fish assemblage structure: inferences based on taxonomic vs. functional groups. *Journal of Biogeography* **34** (2) 324-338.

JUNK WJ, BAYLEY PB and SPARKS RE (1989) The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences* **106** (1) 110-127.

KOLDING J and VAN ZWIETEN PA (2012) Relative lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. *Fisheries Research* **115** 99-109.

MARRIOTT SP (1997) Fisheries institutional reform in developing countries. *Marine Policy* **21** (5) 435-444.

NGUGI CC, MANYALA JO, NJIRU M and MLEWA CM (2009) Some aspects of the biology of the stargazer mountain catfish, *Amphilius uranoscopus* (pfeffer); (Siluriformes: Amphiliidae) indigenous to Kenya streams. *African Journal of Ecology* **47** (4) 606-613.

SANBI (2023a) Available at :http://speciesstatus.sanbi.org/taxa/detail/183/ [Accessed June 1, 2023]

SEEGERS L (2008) The fishes collected by GA Fischer in East Africa in 1883 and 1885/86. *Zoosystematics and Evolution* **84** (2) 149-195.

SKELTON P (1995) *A Complete Guide to the Freshwater Fishes of Southern Africa*. Southern Book Publishers. ISBN 1-86812-350-2.

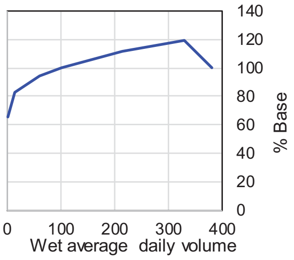
SKELTON P (2001) *A Complete Guide to the Freshwater Fishes of Southern Africa*.

WELCOMME RL (1985) *River fisheries* (No. 262). FAO.

**Note: depending on the hydrology and particular situation and example fish species, higher wet season volumes should be given either a negative or neutral response rather than a positive one:

Wet average daily volume [F season]

	%Base	Y1
Min	0	-2.00
Min Base	15	-1.00
	60	-0.30
Median	100	0.00
	215	0.85
Max Base	330	1.30
Max	380	0.00



3.7.2 *Quiet vegetated waters dependent fish*

Fish that prefer and inhabit quiet vegetated waters in river littorals, backwaters, floodplains (Table 3.55).

Examples: *Coptodon rendalli*, *Enteromius trimaculatus*, *Lacustricola katangae*, *Enteromius paludinosus*, *Tilapia sparrmanii, Pseudocrenilabrus philander*.

Indicator spp for worked example: *Coptodon rendalli* (previously *Tilapia rendalli*), the Redbreast tilapia (family: Cichlidae) has a preference for quiet, well-vegetated water along river littorals or backwaters, floodplains and swamps (FishBase 2023b), with a preference for the Slow Deep velocity-depth class. They are tolerant of a wide range of temperatures (8-

41°C) and salinities. They are important in many fisheries (FishBase 2023b). Note: this species may be exotic in some African systems (e.g. Kouilour-Niara, Republic of Congo).

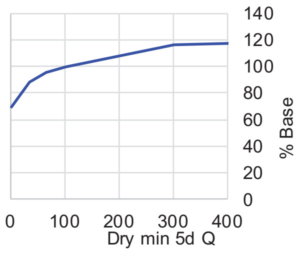
Habitat: Quiet, well-vegetated water along river margins or backwaters.

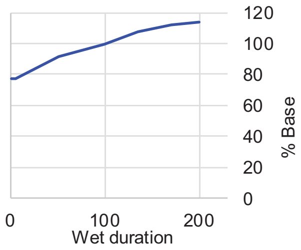
Breeding: A substrate spawner, male and female form pairs to rear the young. Eggs and larvae are usually guarded in a steep-sided circular pit dug in the mud. Occasionally it spawns in large cave-like structures (e.g. in Lake Malawi they are reported to dig a network of tunnels at some sites FishBase 2023b).

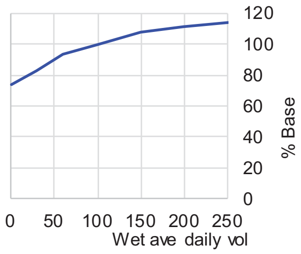
Food: Juveniles feed on plankton, adults on leaves and stems of underwater plants as well as algae, and vegetative detritus, insects and crustaceans (FishBase 2023b; SANBI 2023b).

Links: Dry min 5-day Q; Wet average daily volume; Wet duration; Backwaters and secondary channels; Agg: Aquatic veg; Agg: Marginal and riparian veg; Agg: Invert fish food.

Table 3.55 Quiet vegetated water fish links, explanations and supporting literature

<table>
<tr><td>QUIET VEGETATED WATER FISH</td><td>Indicator species: <i>Coptodon rendalli</i></td></tr>
<tr><td>Links and response curves</td><td>Explanations and supporting literature</td></tr>
<tr><td>Dry min 5d Q [D season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.75</td></tr>
<tr><td>Min Base</td><td>35</td><td>-0.70</td></tr>
<tr><td></td><td>65</td><td>-0.26</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>200</td><td>0.45</td></tr>
<tr><td>Max Base</td><td>300</td><td>1.15</td></tr>
<tr><td>Max</td><td>400</td><td>1.20</td></tr>
</table>


</td><td>Dry min 5-day Q: Reducing dry season flows will reduce accessibility of shallow vegetated habitat, increasing competition and exposure to predation and fishing (Zeug and Winemiller 2008; Kolding and van Zwieten 2012). Oxygen levels may be lowered and temperatures increased, which would impact survival. Higher flows may increase available habitat, spawning and nursery areas, and may reduce predation and fishing pressure (van der Waal 1980; 1996).</td></tr>
<tr><td>Wet duration [W season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.30</td></tr>
<tr><td>Min Base</td><td>5</td><td>-1.30</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>135</td><td>0.50</td></tr>
<tr><td>Max Base</td><td>170</td><td>0.90</td></tr>
<tr><td>Max</td><td>200</td><td>1.00</td></tr>
</table>


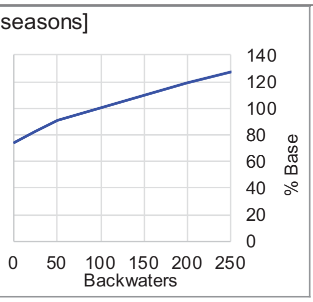
</td><td>Wet duration: The duration of the wet season is particularly important as they occupy the marginal vegetation for breeding and growth (Welcomme 1979; 1985; Junk <i>et al.</i> 1989). The longer the duration of the flood pulse and the amplitude of the flood the greater the opportunities to successfully spawn and grow (Winemiller and Jepsen 1998).</td></tr>
<tr><td>Wet ave daily vol [W season]
<table>
<tr><td></td><td>%Base?</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-1.50</td></tr>
<tr><td>Min Base</td><td>30</td><td>-1.00</td></tr>
<tr><td></td><td>60</td><td>-0.40</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.50</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.85</td></tr>
<tr><td>Max</td><td>250</td><td>1.00</td></tr>
</table>


</td><td>Wet average daily vol: Higher wet season flow will generally make more marginal vegetated habitat available for adults and as spawning and nursery areas (Furse <i>et al.</i> 1979; Hickley and Bailey 1987; Hoeinghaus <i>et al.</i> 2007, Skelton 1995; Macuiane <i>et al.</i> 2009). Lower flows will confine the river more within the channel thereby reducing available habitat. Reduced inundation will reduce recruitment over the wet season. However, beyond a certain point, suitable habitat may be drowned out.</td></tr>
</table>

QUIET VEGETATED WATER FISH	Indicator species: *Coptodon rendalli*
Links and response curves	**Explanations and supporting literature**

Backwaters, secondary channels [All seasons]

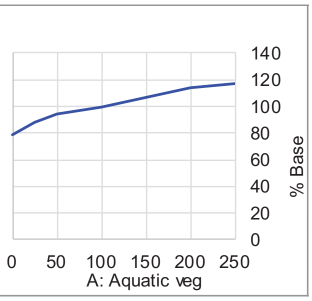
	%Base?	Y1
Min	0	-1.50
Min Base	25	-1.00
	50	-0.50
Median	100	0.00
	150	0.70
Max Base	200	1.30
Max	250	1.60



Backwaters and secondary channels: Prefer to inhabit slow moving water in backwaters and secondary channels.

A: Aquatic veg [All seasons]

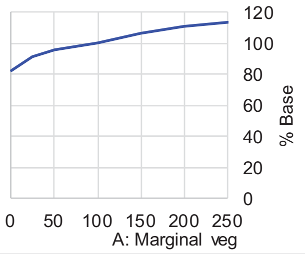
	%Base?	Y1
Min	0	-1.20
Min Base	25	-0.70
	50	-0.35
Median	100	0.00
	150	0.35
Max Base	200	1.00
Max	250	1.20



Agg: Aquatic veg: Provides habitat, especially for juveniles. Increased macrophyte means increased nutrient availability as well as food for as opportunistic macrophytic browsers, resulting in a strong fish year class (Heeg and Breen 1982). In-channel macrophytes such as Nymphaea. Potamogeton, Ceratophyllum, etc. provide habitat and refuge and are often also preferred habitats for invertebrate prey. (Weyl and Hecht 1998)

A: Marginal veg [All seasons]

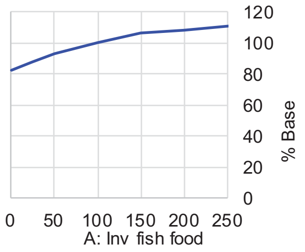
	%Base?	Y1
Min	0	-1.00
Min Base	25	-0.50
	50	-0.25
Median	100	0.00
	150	0.30
Max Base	200	0.80
Max	250	1.00



Agg: Marginal and riparian veg: Marginal vegetation is an important habitat for adult and juvenile cichlids and provides food for herbivores. Reduced inundation of or abundance of these plants would reduce habitat, refuge and food, thereby reducing growth and development of juvenile and adults (Weyl and Hecht 1998).

A: Inv fish food [All seasons]

	%Base?	Y1
Min	0	-1.00
Min Base	25	-0.70
	50	-0.40
Median	100	0.00
	150	0.30
Max Base	200	0.60
Max	250	0.80



Agg: Invert food for fish: Invertebrates form a major component of the food of many fish who live in the in marginal vegetation.

Add or replace substrate / breeding links based on species	See Section 3.7.7
Add or replace food links based on species	See Section 3.7.7

QUIET VEGETATED WATER FISH	Indicator species: *Coptodon rendalli*
Links and response curves	**Explanations and supporting literature**
FISHBASE (2023b) Available at: https://www.fishbase.se/summary/1397 [Accessed June 1, 2023] FURSE MT, KIRK RC, MORGAN PR and TWEDDLE D (1979) Fishes: distribution and biology in relation to changes. In *Lake Chilwa: studies of change in a tropical ecosystem*. Springer Netherlands, Dordrecht. 175-208 pp. HEEG J and BREEN CM (1982) Man and the Pongolo floodplain. National Scientific Programmes Unit: CSIR, SANSP Report 56. 129 pp. HICKLEY P and BAILEY RG (1987) Food and feeding relationships of fish in the Sudd swamps (River Nile, southern Sudan). *Journal of Fish Biology* **30** (2) 147-159. HOEINGHAUS DJ, WINEMILLER KO and BIRNBAUM JS (2007) Local and regional determinants of stream fish assemblage structure: inferences based on taxonomic vs. functional groups. *Journal of Biogeography* **34** (2) 324-338. JUNK WJ, BAYLEY PB and SPARKS RE (1989) The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences* **106** (1) 110-127. KOLDING J and VAN ZWIETEN PA (2012) Relative lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. *Fisheries Research* **115** 99-109. MACUIANE MA, KAUNDA EK, JAMU DM and KANYERERE GZ (2009) Reproductive biology and breeding of Barbus paludinosus and B. trimaculatus (Teleostei: Cyprinidae) in Lake Chilwa, Malawi: implications for fisheries management. *African Journal of Aquatic Science* **34** (2) 123-130. SANBI (2023b) Available at: http://speciesstatus.sanbi.org/assessment/last-assessment/158/ [Accessed June 1, 2023] SKELTON P (1995) A *Complete Guide to the Freshwater Fishes of Southern Africa*. Southern Book Publishers. ISBN 1-86812-350-2. VAN DER WAAL BCW (1980) Aspects of the fisheries of Lake Liambezi, Caprivi. Journal of the Limnological Society of southern Africa, **6** (1) 19-31. VAN DER WAAL BCW (1996) Some observations on fish migrations in Caprivi, Namibia. *Southern African Journal of Aquatic Science* **22** (1-2) 62-80 pp. WELCOMME RL (1979) *Fisheries ecology of floodplain rivers*. Longman, London and New York, USA. 317 pp. WELCOMME RL (1985) *River fisheries* (No. 262). FAO WINEMILLER KO and JEPSEN DB (1998) Effects of seasonality and fish movement on tropical river food webs. *Journal of fish Biology* **53** 267-296. WEYL OLF. and Hecht T (1998) The biology of *Tilapia rendalli* and *Oreochromis mossambicus* (Pisces: Cichlidae) in a subtropical lake in Mozambique. *South African Journal of Zoology* **33** (3) 178-188. ZEUG SC and WINEMILLER KO (2008) Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. *River Research and Applications* **24** (1) 90-102.	

3.7.3 Floodplain dependent fish

These fish depend on, or are most able to take advantage of, the annual inundation of the floodplain for an extended time for spawning, and growing on of juveniles, making lateral migrations onto inundated floodplains to breed (Table 3.56).

Examples: *Schilbe intermedius*, *Enteromius radiatus*, *Enteromius paludinosus*, *Enteromius bifrenatus*, *Enteromius poechii*, *Lacustracola* species, *Marcusenius altisambesi*, *Marcusenius macrolepidotus*, *Labeo lunatus.*

Indicator spp for worked example: *Schilbe intermedius* (Silver catfish, Family: Schilbeidae (Schilbid catfish). They are omnivorous, opportunistic foragers, feeding predominantly on fish (juvenile and adults), but also on insects (aquatic and terrestrial, larvae and adult), molluscs, freshwater prawns and other crustaceans. They are predominantly piscivorous once exceeding 13 cm tail length. They are relatively long lived (observed at 10 years).

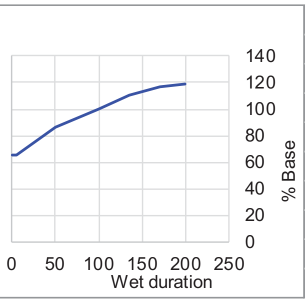
Spawning peaks when flood waters arrive or are receding depending on their location within a system. For example, in the northern Okavango Delta, spawning in the floodplain peaks with the arrival of the annual flood (generally February) and warmer temperatures, whereas in the south, the peak is in October, which is some months after the peak in this area (it arrives around June), but when temperatures are higher. Where feasible, they undertake lateral migration onto floodplains to feed and spawn, and the floodplain provides food and cover for juveniles. They have a relatively high fecundity which increases with body length. They are an important part of commercial, subsistence and recreational fisheries. (Merron and Mann 1995, Reid 1985)

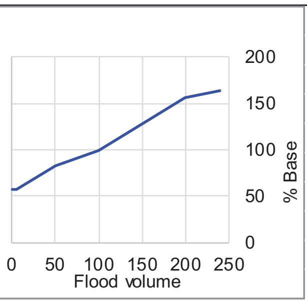
Breeding: Breeds when flood waters and warmer water temperatures are optimal, preferring floodplain and flooded marginal habitats

Food: It is omnivorous, but feeds predominantly on fish and insects.

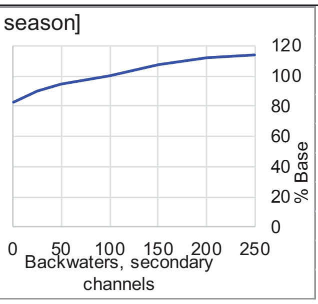
Links: Dry min 5-day Q; Wet duration; Flood volume; Backwaters and secondary channels; Agg: Invert food for fish; Agg: Fish food for fish.

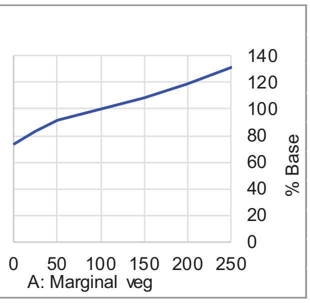
Table 3.56 Floodplain dependent fish links, explanations and supporting literature

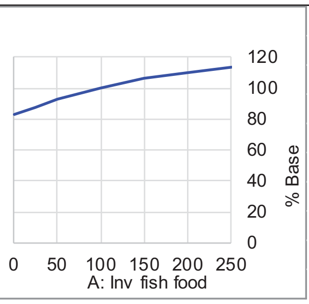
<table>
<tr><td>FLOODPLAIN DEPENDENT FISH</td><td>Indicator species: <i>Schilbe intermedius</i></td></tr>
<tr><td>Links and response curves</td><td>Explanations and supporting literature</td></tr>
<tr><td>Wet duration [W season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2.00</td></tr>
<tr><td>Min Base</td><td>5</td><td>-2.00</td></tr>
<tr><td></td><td>50</td><td>-0.80</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>135</td><td>0.80</td></tr>
<tr><td>Max Base</td><td>170</td><td>1.20</td></tr>
<tr><td>Max</td><td>200</td><td>1.30</td></tr>
</table>


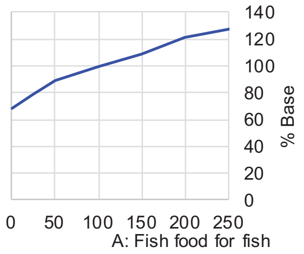
</td><td>Wet duration: The flood duration is important to floodplain dependent fish as they migrate to the floodplain for breeding and growth (Merron and Bruton 1988; Winemiller and Kelso-Winemiller 2003; Welcomme <i>et al.</i> 2006; Peel 2012). The longer the duration of and amplitude of the flood the greater the opportunities to spawn and grow (Welcomme 1979; 1985; Junk <i>et al.</i> 1989). The longer the flood the greater the time the inundated vegetation has to decay and nutrients released to stimulate primary and secondary production (Dumont 1994).</td></tr>
<tr><td>Flood volume [W season]
<table>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2.50</td></tr>
<tr><td>Min Base</td><td>5</td><td>-2.50</td></tr>
<tr><td></td><td>50</td><td>-1.00</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1.60</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.20</td></tr>
<tr><td>Max</td><td>240</td><td>2.30</td></tr>
</table>


</td><td>Flood volume: The extent of flood inundation, which is closely correlated with flood volume, is important to fish using the floodplain during their life cycles. Flooded area is known to be directly linked to productivity and recruitment in fish (Welcomme 1979; 1985; Tweddle 2015).</td></tr>
</table>

<table>
<tr><td>**FLOODPLAIN DEPENDENT FISH**</td><td>Indicator species: *Schilbe intermedius*</td></tr>
<tr><td>**Links and response curves**</td><td>**Explanations and supporting literature**</td></tr>
<tr><td>
Backwaters, secondary channels [W season]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.00</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.60</td></tr>
<tr><td></td><td>50</td><td>-0.30</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.40</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.90</td></tr>
<tr><td>Max</td><td>250</td><td>1.00</td></tr>
</table>


</td><td>Backwaters and secondary channels: Backwaters are an important habitat for fish that shelter in marginal vegetation and floodplains. A reduction in their extent would increase intra and inter-specific competition and reduce growth and survival.</td></tr>
<tr><td>
A: Marginal veg [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.50</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.00</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.60</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.30</td></tr>
<tr><td>Max</td><td>250</td><td>1.70</td></tr>
</table>


</td><td>Agg: Marginal and riparian veg: Most breeding and juvenile floodplain migrants prefer submerged vegetated habitats, which provide or host an abundance of food and serve as a predation refuge (Skelton 2001; Welcomme 1985). Decaying vegetation during the high water level further enriches the detritus, which is a primary food source for some floodplain species (Weyl and Hecht 1998) and a significant proportion of the diet of *Labeo lunatus* during floods (Willoughby and Tweddle 1978).</td></tr>
<tr><td>
A: Inv fish food [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.00</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.70</td></tr>
<tr><td></td><td>50</td><td>-0.40</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.30</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.70</td></tr>
<tr><td>Max</td><td>250</td><td>1.00</td></tr>
</table>


</td><td>*S. intermedius* feeds as both a piscivore and insectivore. It is described as opportunistic forager (Merron and Mann 1995). Younger fish have a more insectivorous diet than larger fish which have a higher percentage of fish in their diet.</td></tr>
<tr><td>
A: Fish food for fish [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.80</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.20</td></tr>
<tr><td></td><td>50</td><td>-0.60</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.65</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.40</td></tr>
<tr><td>Max</td><td>250</td><td>1.60</td></tr>
</table>


</td><td>Agg: Fish abundance. *S. intermedius* feeds as both a piscivore and insectivore. It is described as opportunistic forager (Merron and Mann 1995). Younger fish have a more insectivorous diet than larger fish which have a higher percentage of fish in their diet.</td></tr>
<tr><td>Add or replace substrate / breeding links based on species</td><td>See Section 3.7.7 e.g. *Labeo lunatus* uses the floodplain, but also cobble substrate.</td></tr>
<tr><td>Add or replace food links based on species</td><td>See Section 3.7.7</td></tr>
</table>

FLOODPLAIN DEPENDENT FISH	Indicator species: *Schilbe intermedius*
Links and response curves	**Explanations and supporting literature**

BOKHUTLO T (2011) Life history and stock assessment of *Clarias gariepinus* in the Okavango Delta,Botswana. MSc thesis, Rhodes University. 135 p.

DUMONT HJ (1994) The distribution and ecology of the fresh-and brackish-water medusae of the world. *Studies on the ecology of tropical zooplankton* 1-12.

JUNK WJ, BAYLEY PB and SPARKS RE (1989) The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences* **106** (1) 110-127.

MERRON GS, and BRUTON MN (1988) The ecology and management of the fishes of the Okavango Delta, Botswana, with special reference to the role of the seasonal floods. *JLB Smith Institute of Ichthyology Investigational Report **29*** 1-291.

MERRON GS and MANN BQ (1995) The reproductive and feeding biology of *Schilbe intermedius* Rüppell in the Okavango Delta, Botswana. *Hydrobiologia* **308** (2) 121-129.

PEEL RA (2012) The biology and abundance of three Cichlid species from the Kavango and Caprivi regions, Namibia (Doctoral dissertation). University of Namibia, Namibia

REID GM (1985) A revision of African species of Labeo (Pisces: Cyprinidae) and a re-definition of the genus. Verlag von J. Cramer, Braunschweig. (Ref. 1440) 322 pp.

SKELTON P (2001) *A Complete Guide to the Freshwater Fishes of Southern Africa*.

TWEDDLE D, COWX IG, PEEL RA and WEYL OLF (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology* **22** (1) 99-111.

WELCOMME RL (1979) *Fisheries ecology of floodplain rivers*. Longman, London and New York, USA. 317 pp.

WELCOMME RL (1985) *River fisheries* (No. 262). FAO.

WELCOMME RL, WINEMILLER KO and COWX IG (2006) Fish environmental guilds as a tool for assessment of ecological condition of rivers. *River Research and Applications* **22** (3) 377-396.

WEYL OLF and HECHT T (1998) The biology of *Tilapia rendalli* and *Oreochromis mossambicus* (Pisces: Cichlidae) in a subtropical lake in Mozambique. *South African Journal of Zoology* **33** (3) 178-188.

WILLOUGHBY NG and TWEDDLE D (1978) The ecology of the catfish *Clarias gariepinus* and *Clarias ngamensis* in the Shire Valley, Malawi. *Journal of Zoology* **186** (4) 507-534.

WINEMILLER KO and KELSO-WINEMILLER LC (2003) Food habits of tilapiine cichlids of the Upper Zambezi River and floodplain during the descending phase of the hydrologic cycle. *Journal of fish Biology* **63** (1) 120-128.

3.7.4 Migratory fish (large)

Some fish species migrate up or downstream to reach their spawning, breeding and / or nursery areas. These migrations are distinct from the localised movements to favourable habitats that are common to most species.

Example species: Obligatory migratory: *Anguilla mossambica, Anguilla bengalensis labiata, Anguilla marmorata*. Large bodied riffle dependent migrators: *Labeobarbus codringtonii, Labeobarbus altianalis, Labeobarbus caudovittatus, Labeobarbu kimberlyensis, Labeobarbus marequensis*. Other: *Labeo cylindricus, Labeo molybdinus, Labeo rosae, Labeo congoro, Labeo codringtonii, Hydrocynus vittatus, Enteromius trimaculatus, Enteromius bifrenatus, Micralestes acutidens, Schilbe intermedius, Enteromius afrohamiltoni, Clarias gariepinus*.

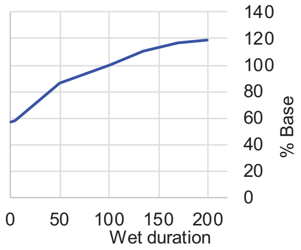
Indicator spp. for worked example: *Anguilla bengalensis labiata*, the African mottled eel, is a subspecies of eel in the genus Anguilla of the family Anguillidae. Showing the typical characteristics of the Anguillidae, this species grows to 1.75 m and as much as 20 kg. It is found in east Africa: Lake Kariba, middle Zambezi, Pungwe, and Buzi river systems, Upper and Lower Save/Rhunde system, Umzingwani and Limpopo Rivers. They inhabit various niches in a river system and penetrate far inland, surmounting formidable barriers in its upstream migration, including the Kariba and Cahora Bassa dams. Adults need moving water to migrate back to the ocean, especially after heavy rains. Caught with various types of nets.

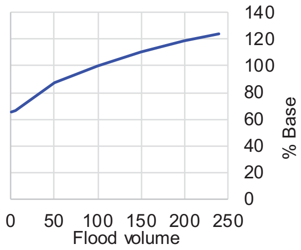
Breeding: Migratory species which breeds in the ocean

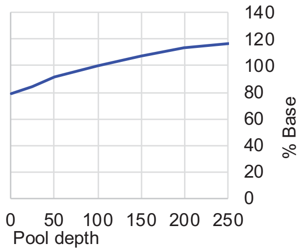
Food: Young fish migrate upstream with a continued feeding mode, especially on invertebrates found on rocks and logs washed by fast moving waters. Their food can also consist of crabs, frogs and even fish, including trout in the streams of the eastern highlands of Zimbabwe.

Links: Wet duration; Flood volume; Pool depth; Agg: Invert food for fish; Migratory fish UPSTREAM SITE; Migratory fish DOWNSTREAM SITE.

Table 3.57 Migratory fish links, explanations and supporting literature

<table>
<tr><td>MIGRATORY FISH</td><td>Indicator species: <i>Anguilla bengalensis labiata</i></td></tr>
<tr><td>Links and response curves</td><td>Explanations and supporting literature</td></tr>
<tr><td>Wet duration [W season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.50</td></tr>
<tr><td>Min Base</td><td>5</td><td>-2.45</td></tr>
<tr><td></td><td>50</td><td>-0.80</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>135</td><td>0.80</td></tr>
<tr><td>Max Base</td><td>170</td><td>1.20</td></tr>
<tr><td>Max</td><td>200</td><td>1.30</td></tr>
</table>


</td><td>Wet duration: The longer the wet duration the greater the chance of elvers reaching this site in the wet season. If shorter, then elvers may only recruit to this site during the wet season of following years. (Seegers <i>et al.</i> 2003)</td></tr>
<tr><td>Flood volume [W season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.00</td></tr>
<tr><td>Min Base</td><td>5</td><td>-1.95</td></tr>
<tr><td></td><td>50</td><td>-0.70</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.80</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.30</td></tr>
<tr><td>Max</td><td>240</td><td>1.50</td></tr>
</table>


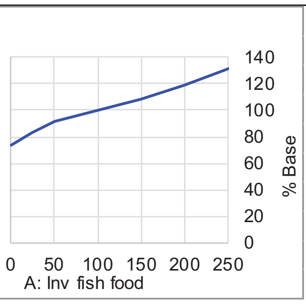
</td><td>Flood volume: Adults need moving water to migrate back to the ocean, especially after heavy rains (Okeyo 1998; Bell-Cross and Minshull 1988).</td></tr>
<tr><td>Pool depth [W season]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.20</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.90</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.40</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.00</td></tr>
<tr><td>Max</td><td>250</td><td>1.20</td></tr>
</table>


</td><td>Pool Depth: Deep pools provide stable habitat for eels post recruitment</td></tr>
</table>

MIGRATORY FISH	Indicator species: *Anguilla bengalensis labiata*
Links and response curves	**Explanations and supporting literature**

A: Inv fish food [All seasons]

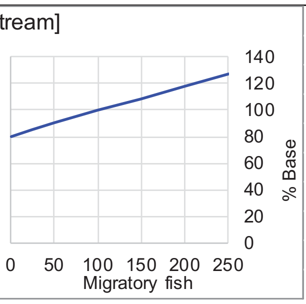
	%Base?	Y1
Min	0	-1.50
Min Base	25	-1.00
	50	-0.50
Median	100	0.00
	150	0.60
Max Base	200	1.30
Max	250	1.70



Agg: Invert food for fish: Young eels migrate upstream with a continued feeding mode, especially on invertebrates found on rocks and logs washed by fast moving waters (Adeney and Hughes 1977)

Migratory fish [All seasons, Site = upstream]

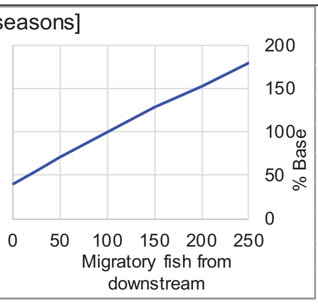
	%Base?	Y1
Min	0	-1.15
Min Base	25	-0.87
	50	-0.57
Median	100	0.00
	150	0.60
Max Base	200	1.25
Max	250	1.60



Obligatory migratory fish at upstream site: Young fish migrate upstream with a continued feeding mode (Okeyo 1998) and penetrate far inland, surmounting formidable barriers in its upstream migration.

Migratory fish from downstream [All seasons]

	%Base?	Y1
Min	0	-3.47
Min Base	25	-2.60
	50	-1.72
Median	100	0.00
	150	1.63
Max Base	200	2.15
Max	250	2.50



Obligatory migratory fish at upstream site: *Anguilla bengalensis labiata* requires access to the ocean as it breeds in the ocean (Okeyo 1998).

Add or replace substrate / breeding links based on species	See Section 3.7.7
Add or replace food links based on species	See Section 3.7.7

SEEGERS L, DE VOS L and OKEYO DO (2003) Annotated checklist of the freshwater fishes of Kenya (excluding the lacustrine haplochromines from Lake Victoria). *Journal of East African Natural History*. **92** (1) 11-47.

OKEYO DO (1998) Updating names, distribution and ecology of riverine fish of Kenya in the Athi-Galana-Sabaki River drainage system. Naga, ICLARM Q **21** (1) 44-53.

BELL-CROSS G and MINSHULL JL (1988) The fishes of Zimbabwe. National Museums and Monuments of Zimbabwe, Harare, Zimbabwe. 294 pp.

ADENEY RJ and HUGHES GM (1977) Some observations on the gills of the sunfish Mola mola. *Journal of the Marine Biological Association of the United Kingdom* **57** (3) 825-837.

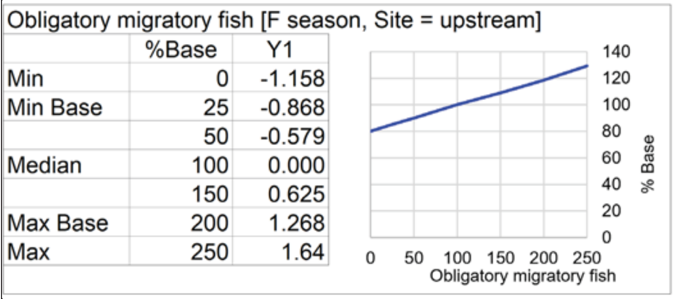
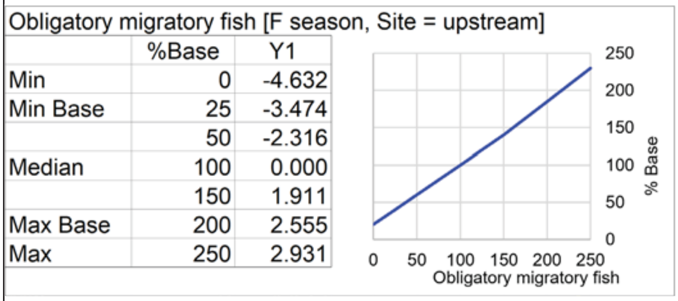
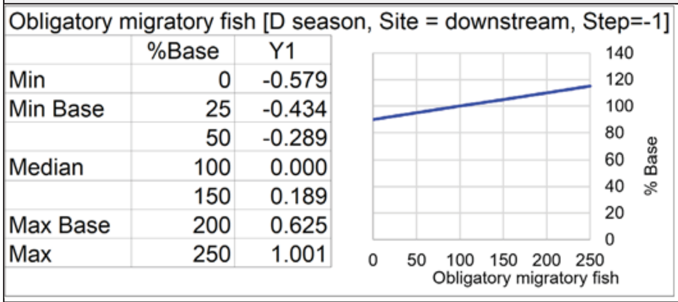
For migratory fish that undertake longer migrations, the habitat and food links and response curves from Table 3.57 should be used, depending on the example species chose, and additional or alternatives can be selected from Section 3.7.7.

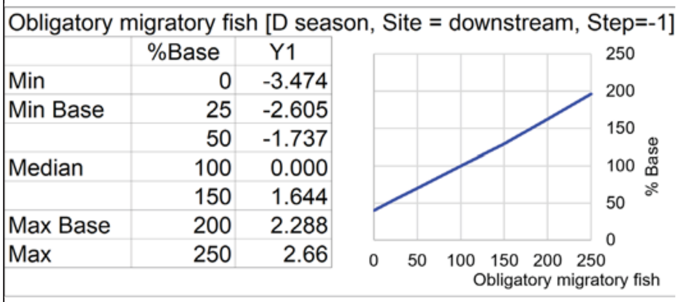
In addition to these links, links are made between sites providing for both up-and downstream movement (Table 3.58)

A positive 1:1 dependence on the abundance at upstream and/or downstream sites would mean that if there were a 10% decline in abundance at the connected site there would be a 10% decline in abundance at the linked site. Similarly, if an instream barrier is modelled in DRIFT to block 40% of the movement between sites, then this will translate into a 40% decline at the linked site. Example response curves are provided and the degree of dependence should be selected/adjusted based on available information. For example, some sub-catchments can be particularly important for specific fish (increasing dependence), whereas others can be less important because appropriate habitats are not present, or may be blocked off due to existing instream barriers such as a steep waterfall (therefore reducing dependence).

It is important to remember that, because of the hierarchical nature of DRIFT calculations, links from downstream sites to upstream sites must be to the previous season or previous year.

Table 3.58 Options for connectivity responses for migratory fish

<table>
<tr><th>Examples of links to upstream sites</th><th>Explanations and supporting literature</th></tr>
<tr><td>
Obligatory migratory fish [F season, Site = upstream]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.158</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.868</td></tr>
<tr><td></td><td>50</td><td>-0.579</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.625</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.268</td></tr>
<tr><td>Max</td><td>250</td><td>1.64</td></tr>
</table>
</td><td>Link to fish at upstream site: Connectivity link with 20% dependence on the upstream reach. A 100% blockage of movement to the upstream reach results in a 20% decrease at the working site. This situation would pertain where an upstream reach was not particularly important to the fish at the working site, for example if the fish's preferred habitats were naturally not very abundance at the upstream site.</td></tr>
<tr><td>
Obligatory migratory fish [F season, Site = upstream]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-4.632</td></tr>
<tr><td>Min Base</td><td>25</td><td>-3.474</td></tr>
<tr><td></td><td>50</td><td>-2.316</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>1.911</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.555</td></tr>
<tr><td>Max</td><td>250</td><td>2.931</td></tr>
</table>
</td><td>Alternate link to fish at upstream site Connectivity link with 80% dependence on the upstream reach. A 100% blockage of movement to the upstream reach results in a 80% decrease at the working site. This situation would pertain where an upstream reach was very important to the fish at the working site, for example if the fish had to migrate to the upstream site to reach critical breeding habitats.</td></tr>
<tr><th>Examples of links to downstream sites</th><th>Explanations and supporting literature</th></tr>
<tr><td>
Obligatory migratory fish [D season, Site = downstream, Step=-1]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.579</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.434</td></tr>
<tr><td></td><td>50</td><td>-0.289</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.189</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.625</td></tr>
<tr><td>Max</td><td>250</td><td>1.001</td></tr>
</table>
</td><td>Connectivity link with a 10% dependence on the downstream site. A 100% increase in the downstream site results in a 10% increase at the working site. This situation would pertain where downstream site was not important to the abundance / survival of the fish at the working site.</td></tr>
</table>

	Alternate connectivity link with 60% dependence on the downstream site. A 100% increase in the downstream site results in a 60% increase at the working site. This situation would pertain where downstream site was important to the abundance / survival of the fish at the working site. For example, the fish's preferred breeding habitat is in abundance at the downstream reach

Obligatory migratory fish [D season, Site = downstream, Step=-1]

	%Base	Y1
Min	0	-3.474
Min Base	25	-2.605
	50	-1.737
Median	100	0.000
	150	1.644
Max Base	200	2.288
Max	250	2.66

3.7.5 *Tolerant fish*

The requirements of generalist fish will often be covered by the above indicators / guilds. However, in a particular river reach these may be more relevant, and the specialist may wish them to be treated separately. In this case the relevant combination of habitats and food from above should be chosen. Negative responses will be muted, and positive response may be larger to reflect their more resilient behaviour (Table 3.59).

Examples: *Clarias gariepinus, Tilapia sparrmanii, Oreochromis mossambicus.*

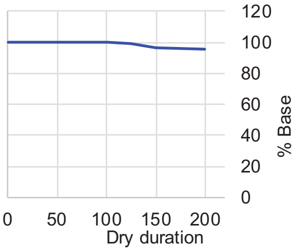
Indicator spp for worked example: *Clarias gariepinus* (Burchell 1822)*:* the African sharptooth catfish (family: Clariidae), is one of the most widely distributed African freshwater fish, naturally found in 8 of the 10 ichthyofaunal regions. Prefers quiet vegetated marginal areas with muddy substrates, and floodplains, but is also found in faster flowing rivers and rapids. It is widely tolerant of extreme environmental conditions. Water parameters appear to play only a very minor role. It is a facultative air-breather, and the presence of an accessory breathing organ enables it to breath air when very active or under very dry conditions. They can leave the water using strong pectoral fins and spines in search of land-based food or to move into breeding areas through very shallow pathways. They migrate to rivers, temporary streams and especially floodplains to spawn, and spawn throughout the flood / rainy season. The adults return to the river or lake soon after, while the juveniles remain in the inundated area, and return once around 2 cm long. It is a popular food fish in Africa.

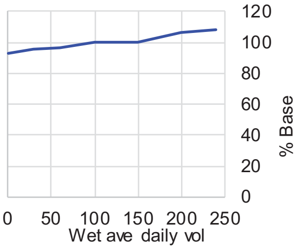
Breeding: During the rainy / flood season in rivers and temporary streams, and especially on inundated floodplains.

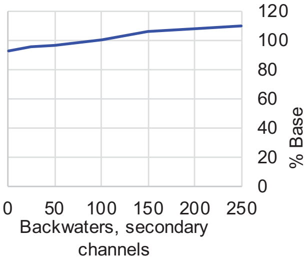
Food: Omnivorous: feed on vegetation, insects, crustaceans and fish, but also young birds, rotting flesh and plants.

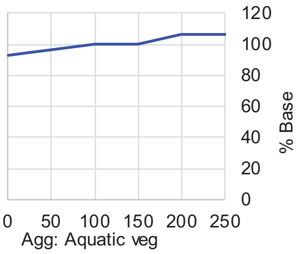
Links: Dry duration; Flood volume; Backwaters and secondary channels; A. Aquatic veg; A. Marginal veg; A. General invert food for fish OR choose a different food depending on chosen indicator species.

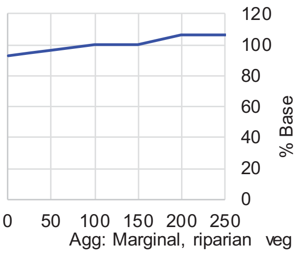
Table 3.59 Tolerant fish links, explanations and supporting literature

<table>
<tr><td>TOLERANT FISH</td><td>Indicator species: <i>Clarias gariepinus</i></td></tr>
<tr><td>Links and response curves:</td><td>Explanation and supporting literature</td></tr>
<tr><td>
Dry duration [W season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>0.10</td></tr>
<tr><td>Min Base</td><td>30</td><td>0.12</td></tr>
<tr><td></td><td>70</td><td>0.12</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>125</td><td>-0.05</td></tr>
<tr><td>Max Base</td><td>150</td><td>-0.20</td></tr>
<tr><td>Max</td><td>200</td><td>-0.25</td></tr>
</table>


</td><td>Dry duration: The dry season is a stressor on the system in general and the longer the dry season, the greater the stressors, which lead to the decline of more sensitive species. Tolerant species are able to cope better with prolonged dry seasons than more sensitive species.</td></tr>
<tr><td>
Wet ave daily vol [W season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.40</td></tr>
<tr><td>Min Base</td><td>30</td><td>-0.25</td></tr>
<tr><td></td><td>60</td><td>-0.18</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.20</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.30</td></tr>
<tr><td>Max</td><td>240</td><td>0.50</td></tr>
</table>


</td><td>Wet ave daily vol: Tolerant species are able to cope with low flows, in the case of Clarias even being able to move overland to find suitable channels or pools.</td></tr>
<tr><td>
Backwaters, secondary channels [W season]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.40</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.25</td></tr>
<tr><td></td><td>50</td><td>-0.18</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.30</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.55</td></tr>
<tr><td>Max</td><td>250</td><td>0.75</td></tr>
</table>


</td><td>Backwaters and secondary channels: Tolerant fish are very often found in the habitat away from main channels to exploit habitat that not many other species find tolerable.</td></tr>
<tr><td>
Agg: Aquatic veg [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.40</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.30</td></tr>
<tr><td></td><td>50</td><td>-0.20</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.20</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.25</td></tr>
<tr><td>Max</td><td>250</td><td>0.35</td></tr>
</table>


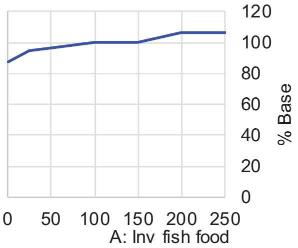
</td><td>Agg. Aquatic veg: Aquatic vegetation provides cover, shade, refugia, and places for egg attachment, as well as larvae attachment and juvenile nurseries (Bruton 1979).</td></tr>
<tr><td>
Agg: Marginal, riparian veg [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-0.40</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.30</td></tr>
<tr><td></td><td>50</td><td>-0.20</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.15</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.25</td></tr>
<tr><td>Max</td><td>250</td><td>0.35</td></tr>
</table>


</td><td>Agg. Aquatic veg: Aquatic vegetation provides cover, shade, refugia, and places for egg attachment, as well as larvae attachment and juvenile nurseries (Bruton 1979).</td></tr>
</table>

TOLERANT FISH	Indicator species: *Clarias gariepinus*
Links and response curves:	**Explanation and supporting literature**

A: Inv fish food [All seasons]

	%Base?	Y1
Min	0	-0.70
Min Base	25	-0.30
	50	-0.18
Median	100	0.00
	150	0.15
Max Base	200	0.25
Max	250	0.35



Agg. Invert food for fish: *Clarias gariepinus* eats a wide range of food including insects.

Add or replace substrate / breeding links based on species	See Section 3.7.7
Add or replace food links based on species	See Section 3.7.7

BRUTON MN (1979) The breeding biology and early development of *Clarias gariepinus* (Pisces: Clariidae) in Lake Sibaya, South Africa, with a review of breeding in species of the subgenus Clarias (Clarias). *The Transactions of the Zoological Society of London* **35** (1) 1-45.

3.7.6 Agg: Fish abundance

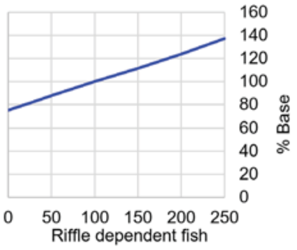
This indicator is a combination of the outcomes for several fish indicators and is provided for ease of reference to the estimated total abundance of the fish (Table 3.60) to be available as a link for other indicators, for example, the Social indicator: Fishing resources has a link to Agg: Fish abundance..

Table 3.60 Constituent links for aggregate indicator Fish abundance

Agg: FISH ABUNDANCE	Combined indicator: Riffle, Quiet vegetated waters, Floodplain, Migratory and Tolerant fish.
Link and response curve	**Explanation and supporting literature**

Riffle dependent fish [All seasons]

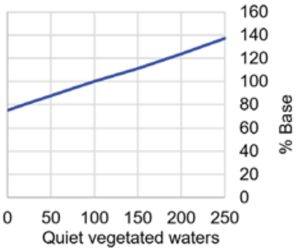
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852



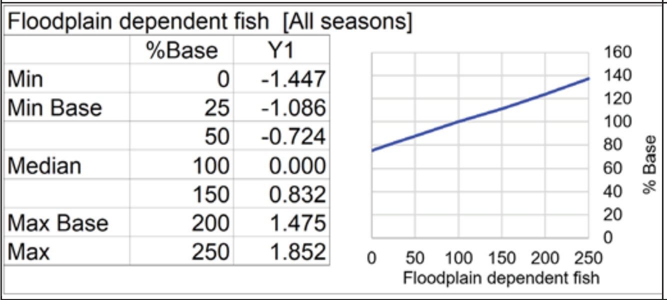
Riffle dependent fish (if relevant): Straight-line relationship with Riffle dependent fish.

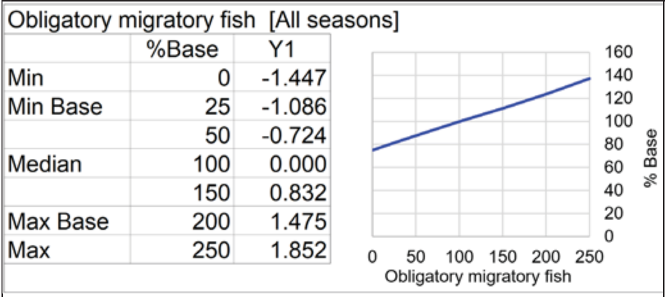
Quiet vegetated waters dependent fish [All seasons]

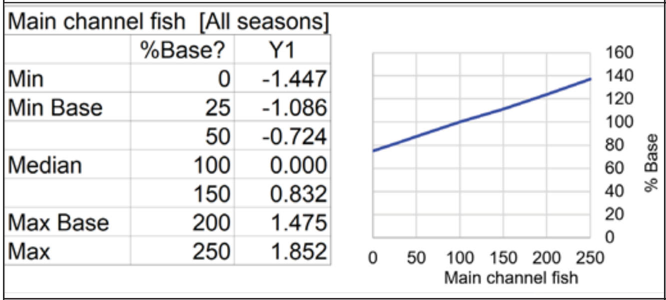
	%Base	Y1
Min	0	-1.447
Min Base	25	-1.086
	50	-0.724
Median	100	0.000
	150	0.832
Max Base	200	1.475
Max	250	1.852

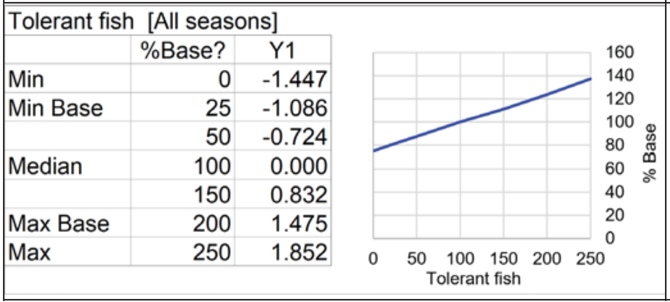


Quiet vegetated waters dependent fish (if relevant): Straight-line relationship with Quiet vegetated waters dependent fish.

<table>
<tr><td>Agg: FISH ABUNDANCE</td><td>Combined indicator: Riffle, Quiet vegetated waters, Floodplain, Migratory and Tolerant fish.</td></tr>
<tr><td>Link and response curve</td><td>Explanation and supporting literature</td></tr>
<tr><td>

Floodplain dependent fish [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Floodplain dependent fish (if relevant): Straight-line relationship with Floodplain dependent fish.</td></tr>
<tr><td>

Obligatory migratory fish [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Obligatory migratory fish (if relevant): Straight-line relationship with Obligatory migratory fish.</td></tr>
<tr><td>

Main channel fish [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Main channel fish (if relevant): Straight-line relationship with Main channel fish.</td></tr>
<tr><td>

Tolerant fish [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.447</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.086</td></tr>
<tr><td></td><td>50</td><td>-0.724</td></tr>
<tr><td>Median</td><td>100</td><td>0.000</td></tr>
<tr><td></td><td>150</td><td>0.832</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.475</td></tr>
<tr><td>Max</td><td>250</td><td>1.852</td></tr>
</table>

</td><td>Tolerant fish (if relevant): Straight-line relationship with Tolerant fish.</td></tr>
</table>

3.7.7 Additional or alternative food, breeding habitat and foraging habitat links.

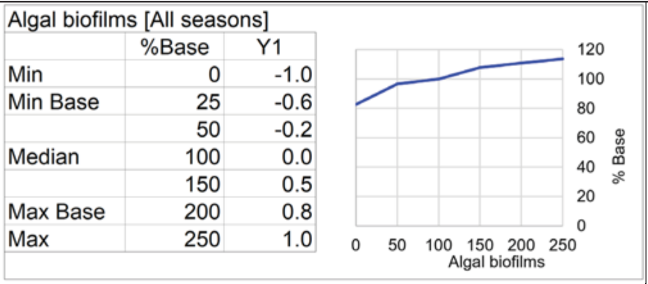
The generic fish indicators are primarily based on preferred flow, geomorphic and vegetation habitat. However, the example fish might differ from basin to basin or from reach to reach. Thus, the relevant food and other link(s) may differ. For example, although invertebrates, particularly baetids and chironomids, are an important food source for many of the riffle dependent species, some riffle dependent species such as *Labeo cylindricus* are grazers and feed on algal biofilms. These alternate links include those for food types (Table 3.61) and breeding habitats (Table 3.62).

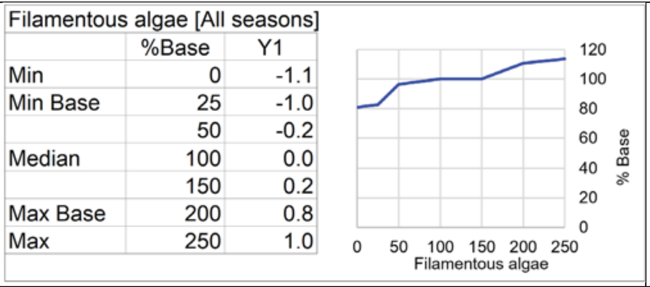
The more specific the requirement of a species, the more sensitive the response will be. For example, a fish that strictly feeds on EPT will have a strong response to changes in EPT; whereas an omnivorous, opportunistic species that feeds on EPT, other insects, detritus, small fish, etc. will have a much less sensitive response to each of these indicators. This is because of two factors:

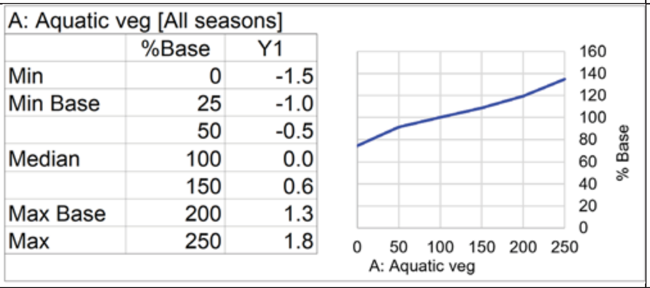
- If multiple links are quantifying the same type of impact, e.g. food availability, the impact will be divided amongst them as the total impact from multiple links is additive; and
- a more generalist species can alter its behavior in case one particular source of food (or habitat) becomes limited.

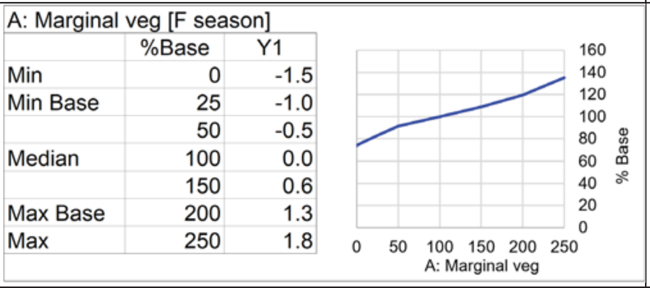
When adding or replacing links, it is good practice is to limit the total number of links to a maximum of ten.

Table 3.61. List of response curves for additional or alternative food for fish

<table>
<tr><th colspan="2">For ALGIVORES</th></tr>
<tr><td>

Algal biofilms [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.0</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.6</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.5</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.8</td></tr>
<tr><td>Max</td><td>250</td><td>1.0</td></tr>
</table>

</td><td>Algal biofilms: Reduced algal abundance will negatively impact growth, development and survival of algivorous fish.</td></tr>
<tr><th colspan="2">For DETRITIVORES</th></tr>
<tr><td>

Filamentous algae [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.1</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.0</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.8</td></tr>
<tr><td>Max</td><td>250</td><td>1.0</td></tr>
</table>

</td><td>Filamentous algae: Filamentous algae is a preferred food of detritivores/shredders (Friberg and Jacobsen 1994).</td></tr>
<tr><td>

A: Aquatic veg [All seasons]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.0</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.3</td></tr>
<tr><td>Max</td><td>250</td><td>1.8</td></tr>
</table>

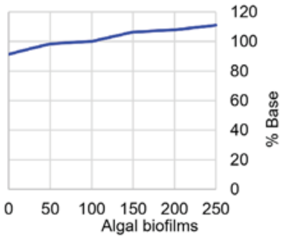
</td><td>Decaying aquatic vegetation enriches the detritus, which provides food for detritivores (Weyl and Hecht 1998)</td></tr>
<tr><td>

A: Marginal veg [F season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.5</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.0</td></tr>
<tr><td></td><td>50</td><td>-0.5</td></tr>
<tr><td>Median</td><td>100</td><td>0.0</td></tr>
<tr><td></td><td>150</td><td>0.6</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.3</td></tr>
<tr><td>Max</td><td>250</td><td>1.8</td></tr>
</table>

</td><td>Decaying marginal vegetation during the high-water level further enriches the detritus, which provides food for detritivores (Weyl and Hecht 1998)</td></tr>
</table>

For HERBIVORES

Algal biofilms [All seasons]

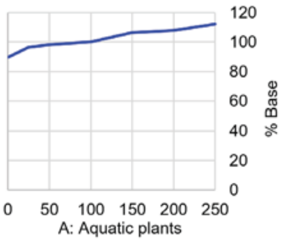
	%Base	Y1
Min	0	-0.5
Min Base	25	-0.3
	50	-0.1
Median	100	0.0
	150	0.3
Max Base	200	0.5
Max	250	0.8



Algal biofilms: Herbivorous fish can graze on algal biofilms. A reduction in abundance will negatively impact growth, development, and survival of these fish.

A: Aquatic plants [All seasons]

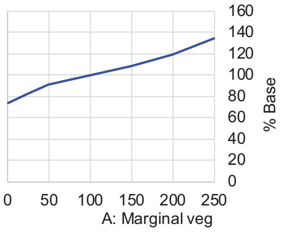
	%Base	Y1
Min	0	-0.6
Min Base	25	-0.2
	50	-0.1
Median	100	0.0
	150	0.3
Max Base	200	0.5
Max	250	0.9



A. Aquatic veg: Aquatic vegetation provide food for herbivores. Reduced inundation of or abundance of these plants would reduce habitat, refuge and food, therefore reducing growth and development of juvenile and adults (Weyl and Hecht 1998).

A: Marginal veg [All seasons]

	%Base?	Y1
Min	0	-1.500
Min Base	25	-1.000
	50	-0.500
Median	100	0.000
	150	0.600
Max Base	200	1.300
Max	250	1.800

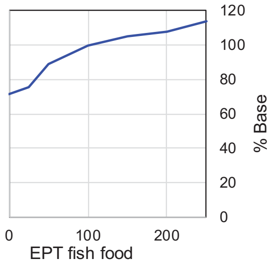


Agg: Marginal and riparian veg: Marginal reeds and shrubs provide food for herbivores. Reduced inundation of or abundance of these plants would reduce habitat, refuge and food, therefore reducing growth and development of juvenile and adults (Weyl and Hecht 1998).

For INSECTIVORES (that prefer EPT)

EPT fish food [All seasons]

	%Base	Y1
Min	0	-1.65
Min Base	25	-1.4
	50	-0.65
Median	100	0
	150	0.2
Max Base	200	0.5
Max	250	1

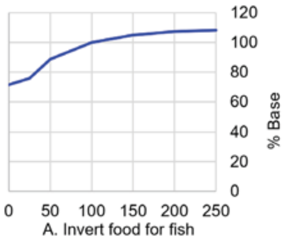


Agg: EPT food for fish: Reduced prey abundance will negatively impact growth, development and survival of insectivorous fish (Marriott 1997, Ngugi *et al.* 2009).

For INSECTIVORES (that most aquatic insects)

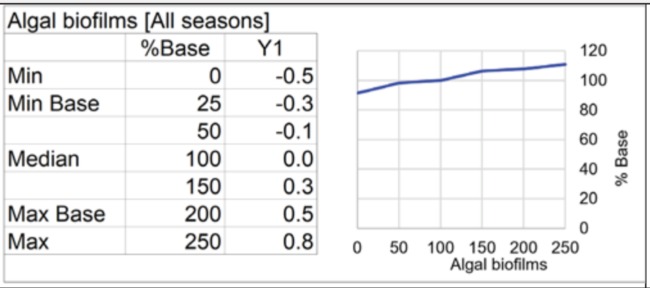
A. Invert food for fish [All seasons]

	%Base	Y1
Min	0	-1.65
Min Base	25	-1.40
	50	-0.65
Median	100	0.00
	150	0.20
Max Base	200	0.45
Max	250	0.55



Agg: Invert food for fish: Reduced prey abundance will negatively impact growth, development and survival of insectivorous fish (Marriott 1997, Ngugi *et al.* 2009).

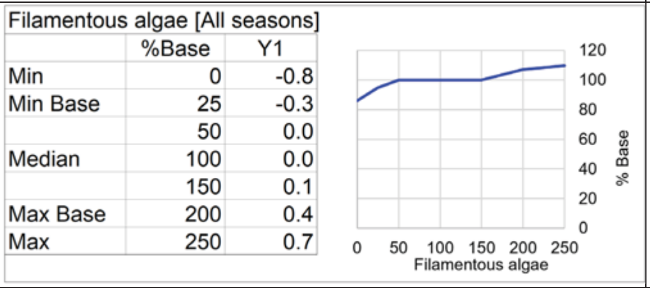
For OMNIVORES (select relevant food types should be chosen from above, example below)



Algal biofilms [All seasons]

	%Base	Y1
Min	0	-0.5
Min Base	25	-0.3
	50	-0.1
Median	100	0.0
	150	0.3
Max Base	200	0.5
Max	250	0.8

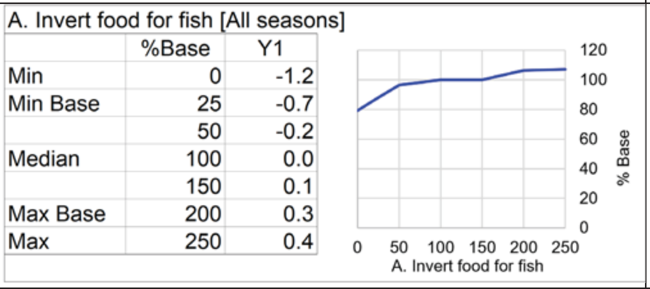
Algal biofilms: Reduced algal abundance will negatively impact growth, development and survival of algivorous fish.



Filamentous algae [All seasons]

	%Base	Y1
Min	0	-0.8
Min Base	25	-0.3
	50	0.0
Median	100	0.0
	150	0.1
Max Base	200	0.4
Max	250	0.7

Filamentous algae: Filamentous algae is a preferred food of detritivores/shredders (Friberg and Jacobsen 1994).

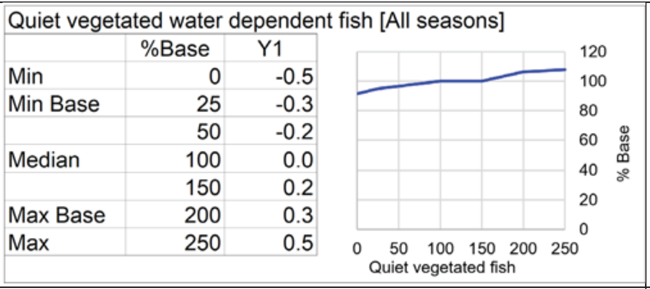


A. Invert food for fish [All seasons]

	%Base	Y1
Min	0	-1.2
Min Base	25	-0.7
	50	-0.2
Median	100	0.0
	150	0.1
Max Base	200	0.3
Max	250	0.4

Agg: Invert food for fish: Reduced prey abundance will negatively impact growth, development and survival of insectivorous fish (Marriott 1997, Ngugi *et al.* 2009).

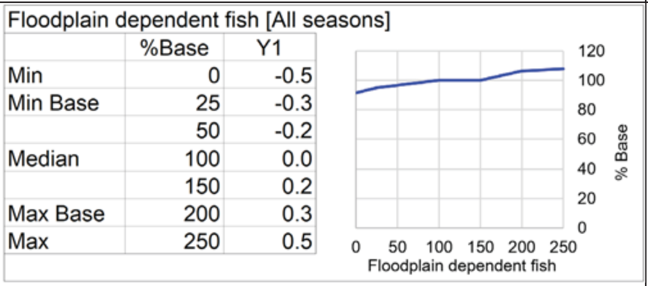
For PISCIVORES (select relevant links from other fish indicators, e.g. Quiet vegetated water dependent fish)



Quiet vegetated water dependent fish [All seasons]

	%Base	Y1
Min	0	-0.5
Min Base	25	-0.3
	50	-0.2
Median	100	0.0
	150	0.2
Max Base	200	0.3
Max	250	0.5

Quiet vegetated water dependent fish: These fish are fierce hunters and tend to eat whatever fish is most available. Reduced prey abundance will negatively impact growth, development and survival.



Floodplain dependent fish [All seasons]

	%Base	Y1
Min	0	-0.5
Min Base	25	-0.3
	50	-0.2
Median	100	0.0
	150	0.2
Max Base	200	0.3
Max	250	0.5

Floodplain dependent fish: These fish are fierce hunters and tend to eat whatever fish is most available. Reduced prey abundance will negatively impact growth, development and survival.

WEYL OLF and HECHT T (1998) The biology of *Tilapia rendalli* and *Oreochromis mossambicus* (Pisces: Cichlidae) in a subtropical lake in Mozambique. *South African Journal of Zoology* **33** (3) 178-188.

FRIBERG N and JACOBSEN D (1994) Feeding plasticity of two detritivore-shredders. *Freshwater Biology* **32** (1) 133-142.

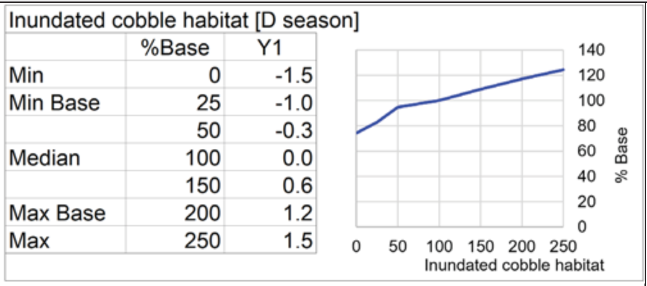
MARRIOTT SP (1997). Fisheries institutional reform in developing countries. *Marine Policy* **21** (5) 435-444.

NGUGI CC, MANYALA JO, NJIRU M and MLEWA CM. 2009. Some aspects of the biology of the stargazer mountain catfish, *Amphilius uranoscopus* (pfeffer); (Siluriformes: Amphiliidae) indigenous to Kenya streams. *African Journal of Ecology* **47** (4) 606-613.

Several of the links in Sections 3.7.1 to Section 0 already include breeding habitat links. However, if additional or alternative links are relevant because of the choice of the indicator fish species, the links in Table 3.62 can be considered for inclusion.

Table 3.62 List of additional or alternative habitat response curves for fish

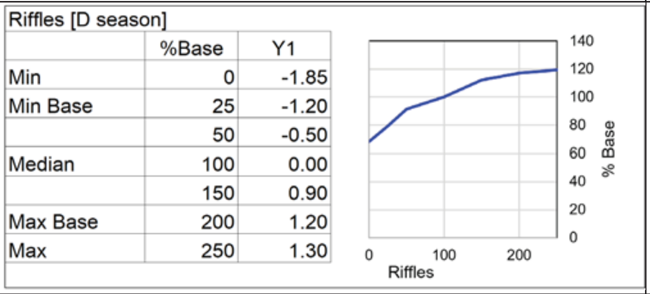
COBBLE AND GRAVEL BEDS (use one)



Inundated cobble habitat [D season]

	%Base	Y1
Min	0	-1.5
Min Base	25	-1.0
	50	-0.3
Median	100	0.0
	150	0.6
Max Base	200	1.2
Max	250	1.5

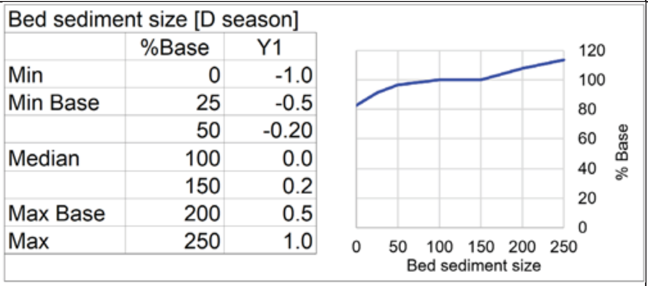
Inundated cobble habitat: The area of inundated gravel and cobble habitat determine the available space for spawning.



Riffles [D season]

	%Base	Y1
Min	0	-1.85
Min Base	25	-1.20
	50	-0.50
Median	100	0.00
	150	0.90
Max Base	200	1.20
Max	250	1.30

Riffles: Riffles are a source of high-quality cobble or rocky habitat and diverse fauna; therefore, an increased frequency of occurrence greatly enhances the diversity of the stream community. Riffle dependent fish are sensitive to the area of riffle habitat available at a site.

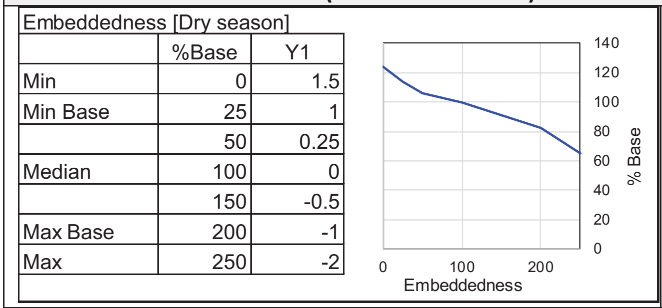


Bed sediment size [D season]

	%Base	Y1
Min	0	-1.0
Min Base	25	-0.5
	50	-0.20
Median	100	0.0
	150	0.2
Max Base	200	0.5
Max	250	1.0

Bed sediment size: Rocky specialist fish are habitat specialists confined to rocky rapid sections with fast flows in shallow to deep waters. These species generally utilize rocky substrates as cover. Thus, they prefer large sediment types, coble, boulders and bedrock.

COBBLE AND GRAVEL BEDS (additional factors)

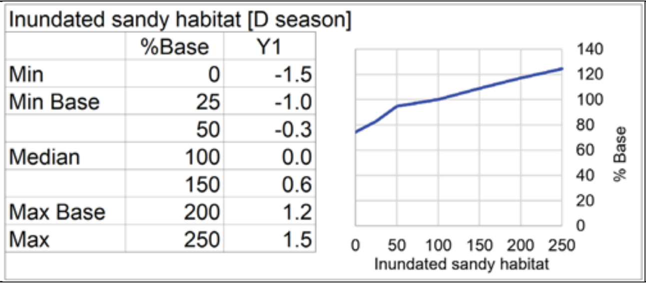


Embeddedness [Dry season]

	%Base	Y1
Min	0	1.5
Min Base	25	1
	50	0.25
Median	100	0
	150	-0.5
Max Base	200	-1
Max	250	-2

Embeddedness: Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered, or sunken into the silt, sand, or mud of the stream bottom. Generally, as rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning and egg incubation.

SOFT SUBSTRATE BEDS



Inundated sandy habitat [D season]

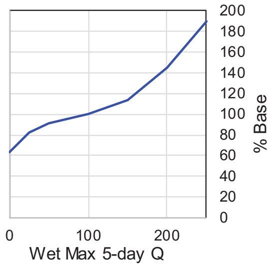
	%Base	Y1
Min	0	-1.5
Min Base	25	-1.0
	50	-0.3
Median	100	0.0
	150	0.6
Max Base	200	1.2
Max	250	1.5

Inundated sandy habitat: Species create sand nests on the outer margins of the river in sandy habitat.

FLOODPLAIN OR INUNDATED MARGINAL HABITAT

Wet Max 5-day Q [Flood season]

	%Base	Y1
Min	0	-2.1
Min Base	25	-1
	50	-0.5
Median	100	0
	150	1
Max Base	200	2
Max	250	2.6

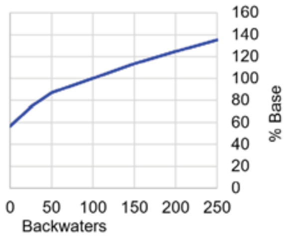


Wet max 5-day Q: The larger the flood peak, the more flooding of the floodplain, the more space, food, breeding success. Flooded area is known to be directly linked to productivity and recruitment in fish (Welcomme 1979; 1985).

BACKWATERS AND SECONDARY CHANNELS

Backwaters and secondary channels [All seasons]

	%Base?	Y1
Min	0	-2.5
Min Base	25	-1.5
	50	-0.75
Median	100	0.0
	150	1.0
Max Base	200	1.5
Max	250	1.8

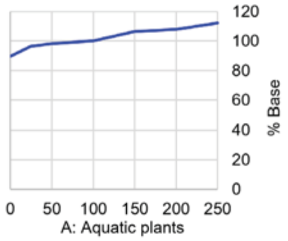


Backwaters and secondary channels: Prefer to inhabit slow moving water in backwaters and secondary channels.

VEGETATION AND/OR BUBBLE/ FOAM NEST HABITAT

A: Aquatic plants [All seasons]

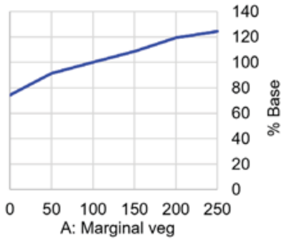
	%Base	Y1
Min	0	-0.6
Min Base	25	-0.2
	50	-0.1
Median	100	0.0
	150	0.3
Max Base	200	0.5
Max	250	0.9



A. Aquatic plants: Bubble nests, also called foam nests, are floating masses of bubbles blown with an oral secretion, saliva bubbles that are often attached to plants. More plants – means more surface area for constructing bubble nests. It also means more protection from the current along the banks.

A: Marginal veg [F season]

	%Base	Y1
Min	0	-1.5
Min Base	25	-1.0
	50	-0.5
Median	100	0.0
	150	0.6
Max Base	200	1.3
Max	250	1.5



Agg: Marginal and riparian veg: Bubble nests, also called foam nests, are floating masses of bubbles blown with an oral secretion, saliva bubbles that are often attached to plants. More plants – means more surface area for constructing bubble nests. It also means more protection from the current along the banks.

3.8 Social

Social use of the river can lead to pressures onto the river ecosystem (Best 2019; Hale *et al.* 2019). However, these feedback loops are not captured in the current set of indicators and response curves. This is because the level of pressures, the current condition of the ecosystem, and the capacity of the ecosystem to withstand social pressures are highly site specific.

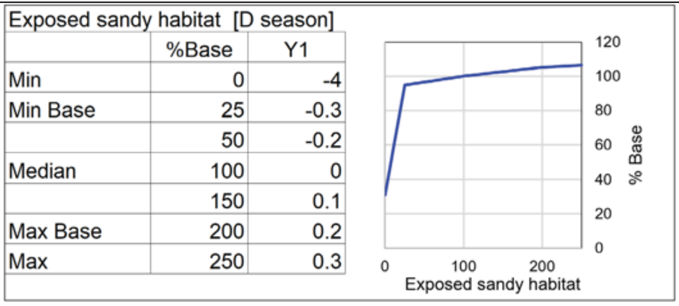
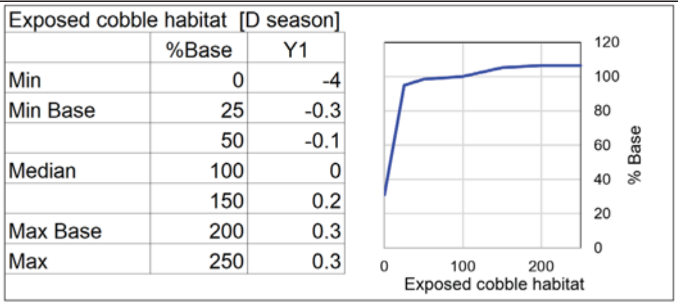
3.8.1 Sand and gravel resources

Sand and gravel beds form through natural processes like erosion, weathering, and sediment transport. Rivers carry sediments downstream, and these materials settle in areas where the water flow decreases. Sand and gravel beds provide important habitats for various aquatic organisms. Many fish species, insects, and other invertebrates use these areas for spawning, shelter, and feeding.

Sand and gravel are valuable resources for construction and industrial purposes. This leads to human interactions such as mining and extraction from riverbeds (Table 3.63). Unregulated or excessive mining can disrupt the natural balance of river ecosystems, leading to habitat degradation, altered sediment transport, and decreased water quality:

Purpose:	Sand and gravel are essential components in the production of concrete, asphalt, and other construction materials. The river bed is often an accessible source of sands and gravels. Further, when people extract sand and gravel from rivers, it can disrupt the natural flow of the water, erode riverbanks, and harm aquatic ecosystems.
Links:	Exposed sandy habitat in the dry season; Exposed cobble habitat in the dry season.

Table 3.63 Sand and gravel mining links, explanations and supporting literature

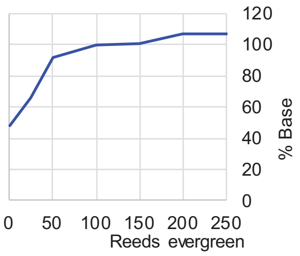
<table>
<tr><th colspan="2">SAND AND GRAVEL RESOURCES</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
Exposed sandy habitat [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-4</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.3</td></tr>
<tr><td></td><td>50</td><td>-0.2</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.1</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.2</td></tr>
<tr><td>Max</td><td>250</td><td>0.3</td></tr>
</table>
</td><td>A decrease in the exposed sandy habitat will mean that there would be less opportunity for mining. An increase would probably attract opportunistic mining along the river.</td></tr>
<tr><td>
Exposed cobble habitat [D season]
<table>
<tr><th></th><th>%Base</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-4</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.3</td></tr>
<tr><td></td><td>50</td><td>-0.1</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>0.2</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.3</td></tr>
<tr><td>Max</td><td>250</td><td>0.3</td></tr>
</table>
</td><td>A decrease in the exposed cobble habitat will mean that there would be less opportunity for mining. An increase would probably attract opportunistic mining along the river.</td></tr>
</table>

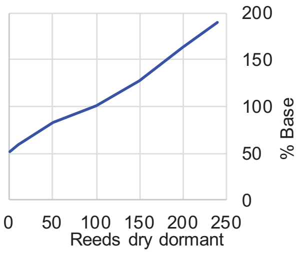
3.8.2 Reed harvesting

Reed harvesting from rivers for subsistence is a seasonal and community-oriented practice, involving the identification and hand harvesting of mature reeds along riverbanks (Table 3.64). Typically done with traditional tools and techniques, the harvested reeds serve multiple purposes within the community, such as construction materials, crafts, and thatching:

Purpose:	Communities often utilize reeds for various purposes, including construction materials for dwellings, fences, and other structures. Reeds can also be woven into mats, baskets, and thatching material for roofs, contributing to local craftsmanship and cultural practices.
Links:	Reeds evergreen; Reeds dry dormant.

Table 3.64 Reed harvesting links, explanations and supporting literature

<table>
<tr><th colspan="2">REED HARVESTING</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><td colspan="3">Reeds evergreen [D season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-3.00</td></tr>
<tr><td>Min Base</td><td>25</td><td>-2.00</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.20</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.30</td></tr>
<tr><td>Max</td><td>250</td><td>0.40</td></tr>
</table>


</td><td>Reeds evergreen: A decrease in the reeds will mean that there would be less available for harvesting. An increase could attract opportunistic harvesting along the river.</td></tr>
<tr><td>
<table>
<tr><td colspan="3">Reeds dry dormant [D season]</td></tr>
<tr><td></td><td>%Base</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-2.80</td></tr>
<tr><td>Min Base</td><td>10</td><td>-2.40</td></tr>
<tr><td></td><td>50</td><td>-1.00</td></tr>
<tr><td>Median</td><td>100</td><td>0</td></tr>
<tr><td></td><td>150</td><td>1.60</td></tr>
<tr><td>Max Base</td><td>200</td><td>2.30</td></tr>
<tr><td>Max</td><td>240</td><td>2.60</td></tr>
</table>


</td><td>Reeds dry dormant: A decrease in the reeds will mean that there would be less available for harvesting. An increase would probably attract opportunistic harvesting along the river.</td></tr>
</table>

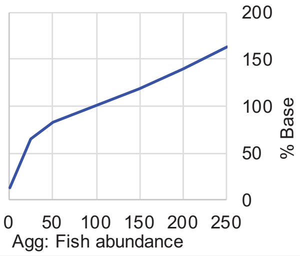
3.8.3 Fishing resources

In river-based settlements, fish often constitute a significant proportion of protein intake, serving as a vital and reliable source of nutrition for the community (Table 3.65). Fishing also supports the livelihoods of individuals involved in the industry. Fishermen, fishmongers, and those engaged in processing and selling fish contribute to the local economy. Abundant fish populations attract tourists interested in recreational fishing. This can stimulate tourism-related activities, providing additional economic benefits to communities. This indicator therefore refers to the resource available for any of these activities:

Purpose: River fish catch sustains communities, providing subsistence, livelihoods, and regional economic contributions.

Links: Agg: Fish abundance.

Table 3.65 Fishing resources links, explanations and supporting literature

<table>
<tr><th colspan="2">FISHING RESOURCES</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
<table>
<tr><td colspan="3">Agg: Fish abundance [All seasons]</td></tr>
<tr><td></td><td>%Base?</td><td>Y1</td></tr>
<tr><td>Min</td><td>0</td><td>-5.00</td></tr>
<tr><td>Min Base</td><td>25</td><td>-2.00</td></tr>
<tr><td></td><td>50</td><td>-1.00</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>1.30</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.90</td></tr>
<tr><td>Max</td><td>250</td><td>2.30</td></tr>
</table>


</td><td>Agg: Fish abundance: The more fish there are, the greater the chance of a good harvest. The average size of the fish is also likely to be larger. Increased fishing effort can counter declines in fish abundance to a point after which the fishing resources becomes unattractive as the effort to catch is not compensated by the value.</td></tr>
</table>

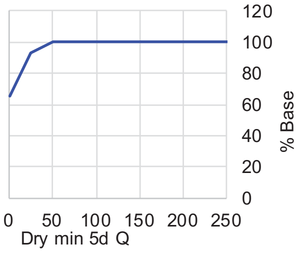
3.8.4 *Aesthetic value*

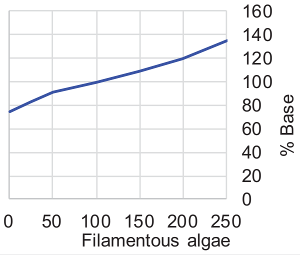
River ecosystems have aesthetic value (and cultural significance in many cases) due to their scenic landscapes and diverse flora and fauna (Table 3.66):

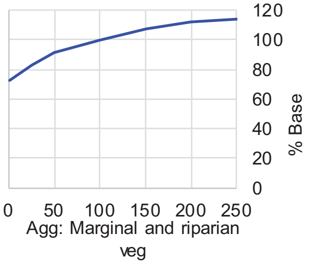
Purpose: The aesthetic value of rivers can determine their attractiveness for recreation, tourism and cultural use.

Links: Dry min 5-day Q; Filamentous algae; Agg: Marginal and riparian veg.

Table 3.66 Aesthetic value links, explanations and supporting literature

<table>
<tr><th colspan="2">AESTHETIC VALUE</th></tr>
<tr><th>Link and response curve</th><th>Explanation and supporting literature</th></tr>
<tr><td>
Dry min 5d Q [Dry season]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-2.00</td></tr>
<tr><td>Min Base</td><td>25</td><td>-0.40</td></tr>
<tr><td></td><td>50</td><td>0.00</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.10</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.10</td></tr>
<tr><td>Max</td><td>250</td><td>0.10</td></tr>
</table>


</td><td>Dry min 5-day Q: Very low flows in a large river are aesthetically unappealing.</td></tr>
<tr><td>
Filamentous algae [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.50</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.00</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.60</td></tr>
<tr><td>Max Base</td><td>200</td><td>1.30</td></tr>
<tr><td>Max</td><td>250</td><td>1.80</td></tr>
</table>


</td><td>Filamentous algae: Large increases in filamentous algae, turning the river eutrophic, will significantly affect aesthetics.</td></tr>
<tr><td>
Agg: Marginal and riparian veg [All seasons]
<table>
<tr><th></th><th>%Base?</th><th>Y1</th></tr>
<tr><td>Min</td><td>0</td><td>-1.60</td></tr>
<tr><td>Min Base</td><td>25</td><td>-1.00</td></tr>
<tr><td></td><td>50</td><td>-0.50</td></tr>
<tr><td>Median</td><td>100</td><td>0.00</td></tr>
<tr><td></td><td>150</td><td>0.50</td></tr>
<tr><td>Max Base</td><td>200</td><td>0.90</td></tr>
<tr><td>Max</td><td>250</td><td>1.00</td></tr>
</table>


</td><td>Agg: Marginal and riparian veg: The aggregate marginal vegetation indicator includes grasses, reeds and riparian shrubs and trees. A reduction in riparian vegetation will affect aesthetics significantly. Marginal vegetation provides shade (and other resources) and increases the aesthetic value of the river</td></tr>
</table>

3.9 Generic modifiers for river indicators

Up to eight modifiers for each indicator are used in the DRIFT software to alter calculations (Table 3.67). These include dependence on the previous year and carrying capacity related factors (Table 3.68).

The modifiers <u>must</u> be completed for DRIFT to work correctly.

Table 3.67 Description of DRIFT modifiers

Modifier	**Dependence on prev year**
Units	%
Description	What percentage of the indicator is dependent on the previous year's abundance?
Further explanation	This modifier captures the extent to which the indicator depends on the end of previous year's abundance. For example, a fish species may be dependent on breeding stock from a previous year, whereas temperature tends to be independent of the previous year's values. 0% dependence means each year restarts at 100% of baseline. 70% dependence means that only 30% will be contributed from the first season of this year.
Modifier	**Increase from %< Base**
Units	years
Description	How long would it take to return to median from 5% of baseline abundance if conditions were at median?
Further explanation	Depending on the indicator, there might be a quick or slow return to Baseline values when abundance is very low compared to the baseline. For example, in a very dry year, macroinvertebrate populations may decline significantly but, because they are short-lived and recolonise rivers each year, once driver conditions improve to average, their numbers may improve quickly to Baseline levels.
Modifier	**Decrease from %> Base**
Units	years
Description	How long would it take to return to median from 200% of baseline abundance if conditions were at median?
Further explanation	Depending on the indicator, there might be a quick or slow return to Baseline values when abundance is much higher than the baseline.
Modifier	**Minimum % of Base**
Units	%
Description	The minimum percentage of Baseline that a population can fall to
Further explanation	Certain indicators might never fall to zero; if the calculated abundance falls below the minimum the abundance is set to the minimum.
Modifier	**Maximum % of Base**
Units	%
Description	The maximum percentage of Baseline that a population can reach
Further explanation	Certain indicators will never increase in abundance above a certain point. For example, the area of lakes may be capped by its physical boundaries. If the calculated abundance rises above the maximum the abundance is set to the maximum.
Modifier	**Upper limit modifier**
Units	0-1
Description	If abundance is high, degree to which rate of increase is slowed down
Further explanation	In many populations, the population growth rate may depend on the population size, such that when the population is high, growth rate is low or even negative as carrying capacity is reached.
Modifier	**Lower limit modifier**
Units	0-1
Description	If abundance is low, degree to which rate of increase is increased
Further explanation	In many populations, the population growth rate may depend on the population size, such that when the population is low, the growth rate is high.
Modifier	**Lag period**
Units	years
Description	The lag effect modifier is intended to allow for the previous years' results to affect the overall result for the year in question.

Further explanation	The lag is calculated using a weighted average of the X previous years. When calculated, more recent years have a larger effect on the outcome than years that are further removed. The weights for a five-year lag period are 0.33, 0.27, 0.2, 1.3, and 0.7 (from year 5 to year 1)

Table 3.68 Generic modifiers for indicators in the generic library

Indicator	**Dependence on prev. year (%)**	**Increase from %< Base (years)**	**Decrease from %> Base (years)**	**Minimum % of Base (%)**	**Maximum % of Base (%)**	**Upper limit modifier (0-1)**	**Lower limit modifier (0-1)**	**Lag period (years)**
Geomorphology								
Clay and silt	0	1	1	0	2000	-	-	-
Sand	20	1	1	0	2000	-	-	-
Gravel and cobble	90	1	1	0	2000	-	-	-
FPOM	0	1	1	0	2000	-	-	-
Bed erosion	30	1	1	0	2000	-	-	-
Bank erosion	20	1	1	0	2000	-		
Bed sediment size	60	3	5	0	500	-	-	-
Turbidity	0	1	1	-	-	-	-	-
Embeddedness	20	2	2	-	-	-	-	-
Pool depth	60	2	2	30	250	-	-	-
Cut banks	70	6	5	0	500	-	-	-
Islands and bars	80	10	15	0	2000	-	-	-
Backwaters and secondary channels	70	5	4	0	200	-	-	-
Exposed sandy habitat in the dry season	60	1	1	0	2000	-	-	-
Exposed cobble habitat in the dry season	60	1	1	0	300	-	-	-
Exposed bedrock habitat in the dry season	60	1	1	0	300	-	-	-
Inundated sandy habitat	60	2	2	0	2000	-	-	-
Inundated cobble habitat	60	2	2	0	300	-	-	-
Inundated bedrock habitat	60	2	2	0	300	-	-	-
Riffles	40	3	3	-	-	-	-	-
Algae								
Algal biofilms	40	1	1	-	-	-	-	-
Filamentous algae	40	1	1	-	-	-	-	-
Riverine vegetation								
Aquatic plants on rock	70	3	3	-	-	-	-	-
Aquatic plants in sand	60	2	2	-	-	-	-	-
Emergent graminoids	50	1	1	-	-	-	-	-
Wetbank grasses	50	1	1	-	-	-	-	-
Wetbank shrubs/trees	60	2	2	-	-	-	-	-

Indicator	**Dependence on prev. year (%)**	**Increase from %< Base (years)**	**Decrease from %> Base (years)**	**Minimum % of Base (%)**	**Maximum % of Base (%)**	**Upper limit modifier (0-1)**	**Lower limit modifier (0-1)**	**Lag period (years)**
Papyrus	50	1	1	-	-	-	-	-
Reeds evergreen	50	1	1	-	-	-	-	-
Reeds dry dormant	50	1	1	-	-	-	-	-
Floating exotics	60	1	2	-	-	-	-	-
Agg: Aquatic veg	-	-	-	-	-	-	-	-
Agg: Marginal and riparian veg	-	-	-	-	-	-	-	-
Macroinvertebrates								
Caenidae	50	1	1	0	2000	1	1	0
Heptageniidae	50	1	1	0	2000	1	1	0
Oligoneuriidae	50	1	1	0	2000	1	1	0
Ceratopogonidae	50	1	1	0	2000	1	1	0
Chironomidae	50	1	1	0	2000	1	1	0
Simuliidae	25	1	1	0	2000	1	1	0
Elmidae	50	1	1	0	2000	1	1	0
Hydropsychidae	50	1	1	0	2000	1	1	0
Agg: Invert food for inverts	0	1	1	0	2000	0	0	0
Coenagrionidae	50	1	1	0	2000	1	1	0
Gomphidae	50	1	1	0	2000	1	1	0
Perlidae	70	2	2	0	2000	1	1	0
Freshwater snails	40	3	1	0	2000	1	1	0
Atyidae	55	1	1	0	2000	1	1	0
Palaemonidae	60	1	1	0	2000	1	1	0
Agg: EPT food for fish	-	-	-	-	-	-	-	-
Agg: Invert food for fish	-	-	-	-	-	-	-	-
Fish								
Riffle dependent fish (small)	55	2	2	0	1000	1	1	0
Quiet vegetated water fish	55	2	2	0	2000	1	1	0
Floodplain dependent fish	60	2	2	0	2000	1	1	0
Migratory fish (large)	60	2	2	0	2000	1	1	0
Tolerant fish	40	2	2	0	2000	1	1	0
Agg: Fish abundance	0	1	1	0	-	-	-	-
Social								
Sand and gravel resources	80	5	5	0	2000	0	0	0
Reed harvesting	65	3	3	0	2000	0	0	0
Fishing resources	70	3	3	0	2000	0	0	0
Aesthetic value	75	3	3	0	2000	0	0	0

4 GENERIC INDICATORS, LINKS AND RESPONSE CURVES FOR SADC ESTUARIES

Historically the method used for EFlows assessment of estuaries in South Africa is the Resource Directed Measures (RDM) Method for Estuaries (van Niekerk *et al.* 2013), and DRIFT has been used for only one estuary, St Lucia. This meant that, while there is a wealth of literature on generic estuary responses to flow changes, there was no ready source of DRIFT estuary databases that could be used to derive generic DRIFT indicators and response curves. Thus, to achieve the objectives of this project:

1. the historic information gathered for the RDM Method and published literature had to be adapted to make it more compatible with DRIFT
2. an approach to develop generic DRIFT estuary indicators and response curves had to be generated.

To assist in this process, DRIFT was set up for the Pungwe Estuary (Section 5) as part of ongoing consultancy work by Southern Waters and CSIR, and served as a test case for a DRIFT-based estuarine approach. This entailed the translation of the RDM Method into the DRIFT assessment framework, and the development of a suite of DRIFT indicators and response curves for the Pungwe Estuary. This will provide a basis for the further work described below.

The next step in this process was to generalize further to arrive at a set of generic curves applicable for estuaries across SADC, across a wide range of conditions. At this stage, the generic response curves are a hybrid between the RDM Method and DRIFT. For example, the DRIFT external hydrological indicators include seasonal aspects of dry season flows, e.g. the onset of the dry season, duration of the dry season, etc., whereas, for the generic estuary response curves these are combined into a single external driving indicator "baseflow".

In a subsequent step, the DRIFT response curves can be drawn from the appropriate section of the relevant generic estuary curves, depending on the situation in the particular estuary being studied. Notes for this are provided in Volume 2 of this report.

At this stage, the response curves are structured differently for rivers and estuaries. For rivers change is measured against the baseline, and the baseline abundance/ area/ concentration is at 100% and the actual baseline abundance/ area/ concentration is unknown[4]. For the estuaries, 100% represents the maximum abundance/ area/ concentration and 0% is the minimum. As was the case for rivers, the abundance/area/concentration represented by the maximum is estuary specific and thus undefined.

Drawing on the key abiotic indicators applied in South Africa's EFlows methods for estuaries, seven external 'driver' indicators were considered most relevant (van Niekerk *et al.* 2019a), for which externally generated time series would be required, namely:

---

[4] In some cases, it may be known, but is not a requirement of DRIFT.

- Hydrology
- Salinity
- Dissolved oxygen
- Turbidity
- Inorganic nutrients
- Sand (sediment input/load)
- Silt (sediment input/load).

Similarly, the responding ecosystem indicators selected for estuaries were also guided by the context of South African estuary EFlows studies. The relevant indicators applied in their Estuarine Health Index (Turpie *et al.* 2012) were used as a basis for the selection of response indicators and disciplines (Table 4.1). These were sorted into five key eco-social response disciplines:

- Hydrodynamics
- Physical habitat
- Microalgae
- Macrophytes
- Fish
- Social.

The indicators in each of these disciplines, and the response curves that drive them (were not estuary specific) are detailed in the sections below.

Table 4.1 Generic indicators for SADC estuary ecosystems

#	Indicator name	Description
Hydrology		
1	Baseflows	The flows without consideration of the flood flows and includes seasonal no flow, low flow and high flow periods.
2	Floods	Include seasonal freshets, small floods, large floods and droughts.
Biogeochemistry or Water Quality		
1	Salinity	Salinity is the amount of salt dissolved in a body of water. On average, the salinity of the open ocean is 35 g/L or g/kg.
2	Dissolved oxygen (DO)	DO is a measure of how much oxygen is dissolved in the water – the amount of oxygen available to living aquatic organisms.
3	Turbidity	Turbidity is a measure of water clarity.
4	Inorganic nutrients (N & P)	The nutrients nitrogen (N) and phosphorus (P) are elements, and are essential building blocks for plant and animal growth.
Sediment load		
1	Silt (sediment input/load)	Silt is a solid-, dust-like sediment transported and deposited by water. Silt is made up of rock and mineral particles that are larger than clay but smaller than sand.
2	Sand (sediment input/load)	Sand is loose granular material that results from the disintegration of rocks, and consists of particles smaller than gravel but coarser than silt.
Hydrodynamics		
1	Marine connectivity	Related to estuary mouth state (e.g. open, constricted, close).
2	Water levels/Tidal amplitude	The water level variability in estuaries could be from freshwater (fluvial) inflows into the systems, tidal forcing as well as other oceanic influences such as storm surges and wave set-up.

#	Indicator name	Description
3	Water retention	The residence time of water in an estuary (inversely related to the flushing rate).
4	Floodplain inundation	Extent of inundation of the estuarine floodplains.
Physical habitat extent		
1	Intertidal extent	Intertidal habitats are found between the high tide and low tide, experiencing fluctuating influences of land and sea.
2	Supra tidal extent	Part of the estuarine floodplain that is located above the high tide that extends into higher lands and is only inundated under spring tides and during floods.
3	Subtidal volume/extent	Subtidal habitat is the area of an estuary that is permanently covered by water.
4	Sediment structure/grain size	Grain size is the average diameter of clasts (particles) of clastic sediments and rocks and can represent a specific habitat requirement for estuarine flora and fauna.
Microalgae		
1	Phytoplankton	Flora of freely floating, often minute microorganisms that occupy the water column.
2	Benthic microalgae	Photosynthetic microorganisms that grow in the sediment on or in exposed intertidal or submerged surfaces.
3	Harmful algae	Blue green *Microcystis* blooms – usually a result of eutrophication.
Macrophyte		
1	Mangroves	Mangroves are trees that establish are established in the intertidal zone in permanently open estuaries along the west and east coast of Africa.
2	Salt marsh	Saltmarshes are a suite of herbaceous vascular plants that are adapted to endure the extremes of salinity, desiccation and tidal flooding.
3	Submerged macrophytes	Plants that are rooted in both soft subtidal and low intertidal substrate and whose leaves and stems are completely submerged for most states of the tide.
4	Reeds and sedges	A reedbed or reed bed is a natural habitat found in floodplains, waterlogged depressions and estuary channels. Sedges are a grass like plant with triangular stems and inconspicuous flowers, growing typically in wet ground. Sedges are widely distributed throughout temperate and cold regions.
5	Macroalgae	Macroalgae, also known as seaweed, are chlorophyll-containing organisms existing in three main categories green, brown, and red algae.
6	Swamp forests	Swamp forests are freshwater ecosystems associated with estuaries.
Fish		
1	IA. Estuarine residents (breed only in estuaries)	Truly estuarine species, which breed in Southern African estuaries. These are resident species which have not been recorded breeding in the freshwater or marine environment
2	IB. Estuarine residents (breed in estuaries and the sea)	Truly estuarine species, which breed in Southern African estuaries. These are resident species which have marine or freshwater breeding populations
3	IIA. Estuary dependent marine species	Euryhaline marine species which usually breed at sea with the juveniles showing varying degrees of dependence on Southern African estuaries; juveniles for this group are dependent on estuaries as nursery areas.
4	IIB&C. Estuarine associated species	Euryhaline marine species which usually breed at sea with the juveniles showing varying degrees of dependence on Southern African estuaries; juveniles for this group occur mainly in estuaries but are also found at sea (IIB) or occur in estuaries but are more abundant at sea (IIC).
5	III. Marine migrants	Marine species which occur in estuaries in small numbers but are not dependent on these systems
6	IV. Freshwater species	Euryhaline freshwater species that can penetrate estuaries depending on salinity tolerance. Includes some species which may breed in both freshwater and estuarine systems.
7	V. Catadromous species	Obligate catadromous species (eels) which use estuaries as transit routes between the marine and freshwater environments

#	Indicator name	Description
Social		
1	Fisheries value	Estuaries provide nursery areas for numerous species of fishes which are exploited by recreational and commercial harvesting in the inshore marine environment.
2	Plant resource value	Estuarine plants including mangrove, reeds, salt marshes provide fuelwood, timber, charcoal, building and materials. They also may provide flood control and erosion protection.
3	Carbon retention value	Estuary sediments can store carbon more effectively than sediments in forests and, if undisturbed, they can store carbon below ground for thousands of years. Coastal habitats that capture and store this "blue carbon" in marine plants and sediments include mangroves, sea grasses and estuaries.

4.1 External driving indicators for estuaries

Time-series for the requisite external driving indicators would be generated outside DRIFT (e.g. time-series for hydrology, water quality, sediment loads). This section outlines the methods typically used to generate these data when using the RDM Method for estuaries. The methods differ for DRIFT.

4.1.1 Hydrology

An assessment of the hydrology of a system is critical in establishing the extent to which modification in river inflow is responsible for the deviation of ecosystem functionality from natural. Two broad hydrological states are relevant, *viz*.:

- Base- or lowflows
- Floods.

The characteristics of estuaries are mainly influenced by seasonal baseflows, with floods playing a longer-term role, e.g. scouring and erosion of sediment and resetting the salinity regime (Stein *et al.* 2021). Floods, therefore, play a major role in the equilibrium between sedimentation and erosion in estuaries (Beck *et al.* 2004). Large volumes of sediment can be removed in a short time during floods ≥20-year return period, and even floods with a 5-10-year return period can also have a significant influence in physically-confined estuaries. Ecologically relevant characterisation of baseflow and floods are summarised in Table 4.2.

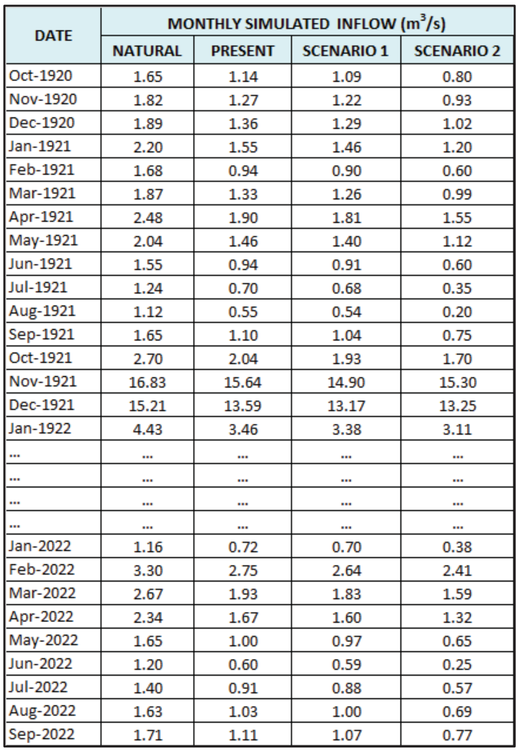
Table 4.2 Key components of baseflow and floods and their associated ecological relevance (modified from Stein *et al.* 2021)

Driver indicator	Key components	Ecological relevance
Baseflow	Seasonal no-flow (cease to flow) periods (natural or due to abstraction), including: ○ Onset of no flow period ○ Duration of no flow period	○ Increase in salinity, hypersaline conditions ○ Increase in the occurrence and duration of mouth closure ○ Low water levels in systems that are close to the sea (decrease in water column depth) ○ Decrease in the open water area ○ Soil salinization ○ Localized die-back of riparian vegetation ○ Loss of marine connectivity in estuaries that close to the sea impacting on biota
	Seasonal low flow periods (especially flows that facilitate salinity creep): ○ Onset of dry season ○ Duration of dry season ○ Lowest flow month ○ Average monthly flow ○ Standard deviation of flow	○ Salinity creep (when open) ○ Mouth closure in systems that are close to the sea (occurrence and duration) ○ Soil salinization ○ Loss of marine connectivity in estuaries that close to the sea impacting on biota
	Seasonal high flow periods: ○ Onset of wet season ○ Duration of wet season ○ Highest flow month ○ Average monthly flow ○ Rate of change in flows ○ Standard deviation of flow	○ Altered marine-estuary connectivity (open mouth) ○ Sediment scouring/deposition ○ Altered reset of water column salinity ○ Altered inundation patterns for supratidal vegetation ○ Altered recruitment signals in the marine environment for invertebrates and fish
Floods	Seasonal Freshets: ○ Frequency ○ Duration ○ Magnitude ○ Rate of change in flows (how fast or how slow)	○ Altered reset of water column salinity ○ Altered inundation patterns for supratidal vegetation ○ Changes to cues for migratory species to move from sea into estuary ○ Changes to recruitment signals for invertebrate and fish
	Small floods (1:2, 1:5, 1:10) resulting in bankfull events: ○ Duration ○ Magnitude (volume or discharge) ○ Rate of change in flows	○ Altered scour of main channels of sediment, accumulated organic matter and sediment pollutants ○ Altered inundation of riparian vegetation ○ Changes to recruitment signals for invertebrates and fish

Driver indicator	**Key components**	**Ecological relevance**
	Major floods (1:10, 1:20, 1:50 and 1:100 year return period) resulting in overbank flood events: ○ Duration ○ Magnitude ○ Rate of change in flows	○ Altered scour of main channels and floodplain of sediment, accumulated organic matter and sediment pollutants ○ Altered reset of sediment erosion/depositional cycles ○ Altered inundation of floodplain vegetation ○ Changes to significant recruitment signals for invertebrates and fish
	Droughts (e.g. 1:10 years or 1:20 year return period): ○ Occurrence ○ Duration ○ Magnitude	○ Increase in salinity, hypersaline conditions ○ Increase in the occurrence and duration of mouth closure ○ Low water levels in estuaries that close to the sea (decrease in water column depth) ○ Decrease in open water area or complete drying of this area ○ Soil salinization ○ Disconnect from catchment ○ Die-back of riparian and submerged vegetation ○ Recruitment failure of invertebrates and fish

RDM Estuary EFlows assessments are primarily driven by long-term river inflow patterns, for example using 70-100 year simulated monthly flows (Table 4.3). River flow is considered the primary driver of determining the physical state configuration in an estuary and depending on the purpose of a study, these are typically provided for natural flows, present flow, and a selection of scenarios, which can then be used to set a desired ecological state and associated EFlows. Monthly simulated flows are typically generated in a hydrological model calibrated for hydrological conditions in a particular catchment. As with the generation of the simulated flows, the various baseflow and flood components (Table 4.3) need to be determined by an experienced hydrologist.

Table 4.3 **Example of simulated monthly flow (m^3/s) table generated at the head of an estuary for a hypothetical natural, present and two alternative scenarios**



DATE	MONTHLY SIMULATED INFLOW (m^3/s)			
	NATURAL	PRESENT	SCENARIO 1	SCENARIO 2
Oct-1920	1.65	1.14	1.09	0.80
Nov-1920	1.82	1.27	1.22	0.93
Dec-1920	1.89	1.36	1.29	1.02
Jan-1921	2.20	1.55	1.46	1.20
Feb-1921	1.68	0.94	0.90	0.60
Mar-1921	1.87	1.33	1.26	0.99
Apr-1921	2.48	1.90	1.81	1.55
May-1921	2.04	1.46	1.40	1.12
Jun-1921	1.55	0.94	0.91	0.60
Jul-1921	1.24	0.70	0.68	0.35
Aug-1921	1.12	0.55	0.54	0.20
Sep-1921	1.65	1.10	1.04	0.75
Oct-1921	2.70	2.04	1.93	1.70
Nov-1921	16.83	15.64	14.90	15.30
Dec-1921	15.21	13.59	13.17	13.25
Jan-1922	4.43	3.46	3.38	3.11
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
Jan-2022	1.16	0.72	0.70	0.38
Feb-2022	3.30	2.75	2.64	2.41
Mar-2022	2.67	1.93	1.83	1.59
Apr-2022	2.34	1.67	1.60	1.32
May-2022	1.65	1.00	0.97	0.65
Jun-2022	1.20	0.60	0.59	0.25
Jul-2022	1.40	0.91	0.88	0.57
Aug-2022	1.63	1.03	1.00	0.69
Sep-2022	1.71	1.11	1.07	0.77

4.1.2 Biogeochemistry (water quality)

Drawing on experience gained, primarily through EFlows determinations using the South African methods for the determination of ecological flow requirements (DWAF 2008), the following key biogeochemical indicators are considered most useful and relevant:

- Salinity
- Dissolved oxygen
- Turbidity
- Inorganic nutrients.

pH is also important but is not suitable for a generic indicators list for the reasons outlined in Box 4.1. Characterisation and motivation for the selection of these indicators are provided in Table 4.4.

Box 4.1 pH as a biogeochemical driver

Ocean acidification and alteration of pH in estuaries because of catchment pollution and excessive eutrophication (e.g. Omarjee *et al.* 2020; 2021) increasingly pose a potential threat to estuarine biota. Also, a marked reduction in inflows to an estuarine lake in South Africa (Verlorenvlei) resulted in marked pH reduction when sediments that have previously been submerged for long periods were first exposed and then re-wetted. Natural sulphate reduction processes can, where sufficient organic matter and iron minerals are available, cause sediment accumulation of sulphide minerals such as pyrite, FeS_2. Then on re-wetting, and exposure to air, the pyrite gets oxidised again to produce sulfuric acid and dissolved ferrous (Fe^{2+}) causing a mark reduction in water pH (Mosley *et al.* 2014). In addition, eutrophication can cause extreme diurnal fluctuations (Feely *et al.* 2010). Therefore, because of human interference, pH is emerging as another possible key driver of change in estuaries. However, variability in pH in estuaries is influenced by an array of chemical and biological processes which makes it very difficult to provide generic patterns of influence. Such information therefore largely relies on measured data in a specific system under different physical states which is rarely available for Southern Africa. If available, such data can be used to construct pH matrices to derive time series outputs, like those described for biogeochemical indicators (e.g. salinity).

Table 4.4 Characterisation and relevance of selected biogeochemical 'driver' indicators

Driver indicator	Description and motivation
Salinity	Salinity is the amount of salt dissolved in a body of water. On average, the salinity of the open ocean is 35 g/L or g/kg. The use of electrical conductivity measurements to estimate the ionic content of seawater led to the development of the scale called the practical salinity scale 1978 (PSS-78). Salinities measured using this do not have units, thus the use of the suffix PSU (practical salinity unit) and parts per thousand (ppt) is formally incorrect. Seawater has a higher density than river water, due to its high salinity. In estuaries where seawater and river water meet, seawater will tend to intrude beneath the river outflow. Salinity is an indicator used to understand the hydrodynamics and mixing processes of an estuary as freshwater mixes with seawater. Salinity is also a key driver in the ecology of an estuary as many organisms can only survive within a limited salinity range. It is thus the key indicator affected by environmental flows into estuaries. In open estuaries, reduced flow is the key driver of increased salinity under low flow conditions. Salinity can be used as a measure of dilution as it is a conservative parameter (not influenced by biological processes) and thus salinity can be utilised as a proxy for any variable deemed to display conservative behaviour.
Dissolved oxygen (DO)	DO is a measure of how much oxygen is dissolved in the water – the amount of oxygen available to living aquatic organisms. Decreases in DO are often related to increased organic load, such as from sewage, algal blooms, and influx of organic matter into an estuary. This increase in organic load can lead to increased bacterial activity, resulting in

Driver indicator	Description and motivation
	greater oxygen consumption. Therefore, the available DO, especially in bottom waters, can become depleted acting as a stressor to the estuary ecology.
Turbidity	Turbidity is a measure of water clarity. Increased turbidity reduces the penetration of light in water and affects the depth at which submerged aquatic vegetation can grow. For instance, seagrasses will not grow in highly turbid environments. Turbidity also impacts the feeding ability of many faunal species as high turbidity may not be conducive to full range of feeding (clogging of feeding parts and gills) and can be related to osmoregulatory interference and salinity tolerance of juveniles. Input from catchments has a significant influence on turbidity distribution patterns in estuaries, depending on the level of freshwater influence in a system. These can be natural, especially during periods of high flows, but also can be because of anthropogenic catchment activities (such as agriculture, mining, and forestry activities) causing sediment erosion and increasing water turbidity. Other activities also can contribute to higher turbidity such as untreated wastewater discharge or algal blooms because of nutrient enrichment.
Inorganic nutrients (N and P)	Dissolved inorganic nutrients (N and P) are critically important from primary production in an estuary, but when systems become nutrient-enriched it can cause eutrophication or excessive plant growth. In estuarine and marine environments inorganic nitrogen is typically considered the limiting nutrient for growth, whereas in freshwater it is mainly phosphorous. Input from catchments has a significant influence on inorganic nutrient patterns in estuaries, depending on the level of freshwater influence in a system. These can be natural, but also can be because of anthropogenic catchment activities (such as agriculture and inappropriate wastewater and urban stormwater treatment). Such activities also can introduce excessive nutrients directly to an estuary associated with activities along the banks.

To generate input for salinity, and other biogeochemical driver indicators (DO, turbidity, and inorganic nutrients) in estuaries, a physical state approach is applied (Van Niekerk *et al.* 2019a; Taljaard *et al.* 2022). This approach primarily aims to simplify and aggregate complex physical processes to temporal and spatial scales that are more suitable for the interpretation of response indicators. The application of this approach within the context of Southern African estuaries is provided by Van Niekerk *et al.* (2023a) as summarised below. In brief, this process involves, identifying typical physical states in an estuary, estimating the water quality parameters corresponding to the physical states (e.g. open/closed mouth state); and then calculating what the state would be (and subsequently what the water quality would be) at different levels of inflow from the river.

4.1.2.1 Typical physical states relevant to Southern African estuaries

Physical states are primarily derived from predictable relationships between river inflow and estuarine characteristics, such as mouth state (open or closed), tidal amplitude and/or water level (high or low), and water column mixing and circulation processes, depicted in salinity regimes. Using these basic characteristics, a range of generic physical states most relevant to Southern African estuaries were developed as illustrated in Figure 4.1.

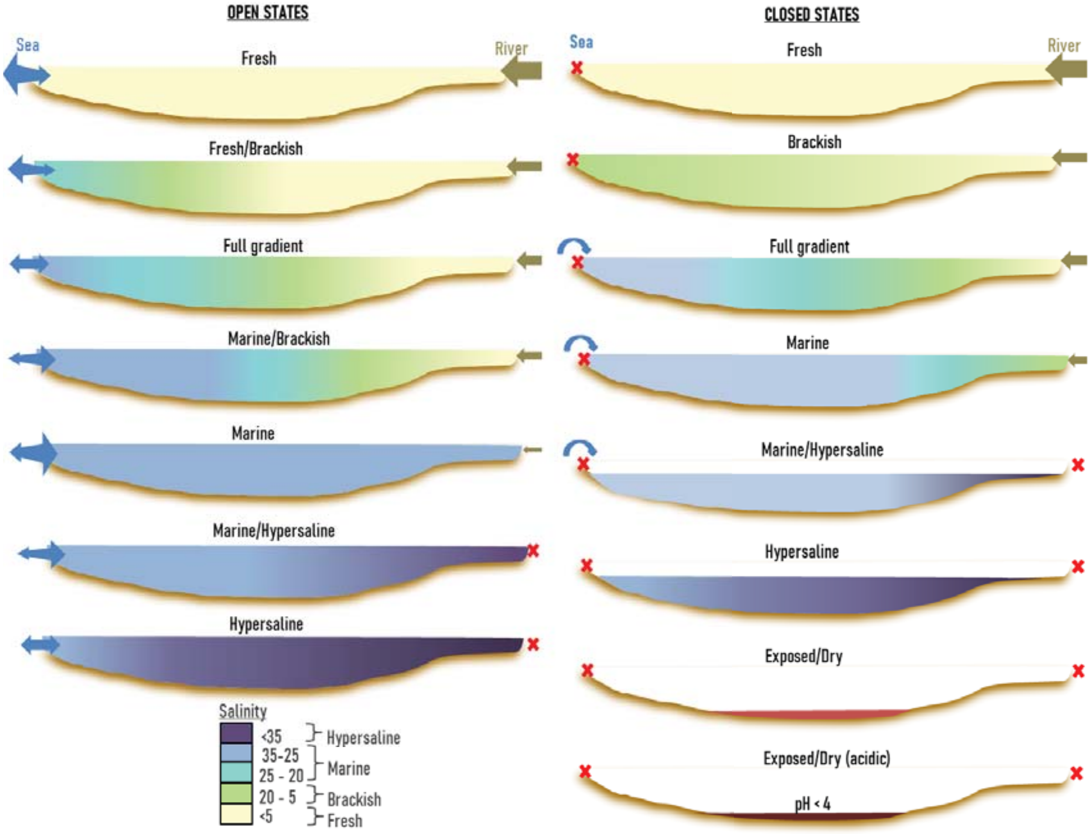


Figure 4.1 **Conceptualisation of various generic physical states relevant to Southern African estuaries, expressed in terms of tidal exchange, mouth state, relative river inflows, water level and salinity regimes (indicative of circulation and mixing processes, as well as evaporation rates) (Source: Van Niekerk *et al.* 2023a)**

Table 4.5 summarises the key characteristics of various generic physical states. Given the high variability in estuary geomorphology in the Southern African region (i.e. size, depth, channel configuration, bathymetry, and topography) it was not possible to identify generic flow ranges coupled to specific physical states. However, it has been possible to identify the component of a flow regime (e.g. low flows or floods) that would typically be associated with specific physical states. By way of example, for the Pungwe Estuary, the monthly flow ranges (Table 4.7) were used to determine daily salinity levels (Table 4.9).

Van Niekerk *et al.* (2023a) provide specific details on the type of generic abiotic states that could be expected across the various ecosystem types as summarised in Table 4.6 and could be consulted in the selection of possible representative physical states for EFlows determinations in specific systems.

Table 4.5 Key characteristics of the generic physical states envisaged for estuaries in the Southern Africa region (Source: Van Niekerk *et al.* 2023a)

PHYSICAL STATE		DRIVING FLOW COMPONENT	TIDE & WATER LEVEL	DOMINANT 'MIXING' PROCESS	WATER RETENTION	SALINITY
Open	**Fresh**	Floods, freshets & seasonal high flows from larger catchments	Tidal, but can have elevated water levels due to flooding for short periods	Fluvial	Low (days)	Nearly/fresh throughout estuary (<5)
	Fresh/Brackish	Seasonal high flows	Tidal	Fluvial, with some tidal mixing	Low (days to weeks)	Limited salinity penetration in lower and middle reaches (< 20) (estuarine zone), some zones can be fresh (<5)
	Full gradient	Seasonal low flows (microtidal), Seasonal high flows (meso-and macrotidal)	Tidal, but constricted along wave-dominated coast	Tidal & Fluvial	Low-Med (weeks)	Full salinity gradient throughout the system (35-0)
	Marine/ Brackish	Seasonal low flows	Tidal, but constricted along wave-dominated coast	Tidal	Med-High	Significant saline penetration, with upper reaches brackish (>15)
	Marine	Seasonal low flows	Tidal, but very constricted along wave-dominated coast	Tidal	High	Marine salinity regime is observed throughout the system (>30)
	Marine/Hyper-saline 35-45	No flows, droughts	Tidal, but very constricted along wave-dominated coast. Some parts may become isolated/dry out.	Tidal & wind (evaporation)	Very high	Salinity regime varies from marine (.30) to hypersaline (<65) in parts of the system
	Hypersaline >45	No flows, droughts	Tidal, but very constricted along wave-dominated coast. Some parts may become isolated/dry out.	Tidal & wind (evaporation)	Very high	Hypersaline (>45)
Closed	**Fresh**	Seasonal low and high flows	High to very high-water levels.	Fluvial, seepage losses	High	Nearly fresh throughout (<5).
	Brackish	Seasonal high flows	High water levels	Fluvial, seepage losses	High	Brackish throughout (<20).
	Full gradient	Seasonal low flows	High water levels	Fluvial, seepage losses, and overwash (from sea)	High	Longitudinal salinity gradient (0-35)
	Marine	Seasonal low flows or no flows	Low water levels.	Overwash, wind (evaporation),	High	Salinity mostly marine (>30) but can be brackish (5-20) in parts of the system.
	Marine/Hyper-saline 35-45	Zero inflows and droughts natural or anthropogenic	Very low water levels, some littoral habitats may be exposed or parts system; isolated from larger system.	Overwash & wind (evaporation)	Very High	Salinity regime varies from marine (> 30) to hypersaline (<45) in parts of the system
	Hypersaline 45-120	Droughts (natural or anthropogenic), No seasonal flows	Very low water levels, some littoral habitats may be exposed, or parts of lakes isolated from larger system.	Wind (evaporation)	Very High	Hypersaline (45-120)
	Hypersaline >120	Droughts (natural or anthropogenic), No seasonal flows	Very low water levels, some littoral habitats may be exposed, or parts of lakes isolated from larger system.	Wind (evaporation)	Very High	Hypersaline (>120)
	Exposed/Dry	Droughts (natural or anthropogenic), No seasonal flows	Very little water remaining, isolated waterbodies	Wind (evaporation)	Very High	Brackish to hypersaline depending on starting conditions
	Exposed/Dry Acidic (pH <4)	Droughts (natural or anthropogenic), No seasonal flows	Very little water remaining isolated waterbodies. Exposed pyritic organic-rich soils along margins or bed	Wind (evaporation)	Very High	Brackish to hypersaline depending on starting conditions

Table 4.6 **Physical States associated with the estuary functional types that occur in Southern Africa (Source: Van Niekerk *et al.* 2023a)**

ESTUARY ECOSYSTEM TYPE	PHYSICAL STATE															
	Open							Closed								
	Fresh	Brackish	Full gradient	Marine/ Brackish	Marine	Hypersaline 35-65	Hypersaline >65	Fresh	Brackish	Full gradient	Marine	Hypersaline 35-65	Hypersaline 65-120	Hypersaline >120	Exposed/Dry	Exposed/Dry Acidic
COOL TEMPERATE																
Estuarine lagoons				●	●	●										
Estuarine bay			●	●	●											
Estuarine lakes	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
Permanently open	●	●	●	●	●	●										
Fluvially dominated*	●	●	●						●							
Intermitted closed	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●
Deltas*	●	●	●	●												
Freshwater coastal lakes	●							●								
Ephemeral															●	
WARM TEMPERATE																
Estuarine lagoons			●	●	●	●										
Estuarine bay			●	●	●											
Estuarine lakes	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Permanently open	●	●	●	●	●	●										
Fluvially dominated*	●	●	●						●							
Intermitted closed	●	●	●	●	●	●		●	●	●	●	●	●			
Deltas*	●	●	●													
Freshwater coastal lakes	●							●								
Ephemeral															●	
SUBTROPICAL																
Estuarine lagoons			●	●	●											
Estuarine bay			●	●	●											
Estuarine lakes	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Permanently open	●	●	●	●	●	●										
Fluvially dominated*	●	●	●					●								
Intermitted closed	●	●	●	●	●			●	●	●	●	●	●			
Deltas*	●	●	●													
Freshwater coastal lakes	●							●								
Ephemeral															●	
TROPICAL																
Estuarine lagoons			●	●	●											
Estuarine bay		●	●	●	●											
Estuarine lakes	●	●	●	●	●	●		●	●	●	●	●				
Permanently open	●	●	●	●												
Fluvially dominated*	●	●	●					●								
Intermitted closed	●	●	●		●			●	●	●	●	●				
Deltas*	●	●	●													
Freshwater coastal lakes	●							●								
Ephemeral															●	

*Note: Functional type is also associated with extensive transitional water states in the nearshore marine environment

4.1.2.2 Determination of salinity and other biogeochemical driver input data

The calculation of salinity and water quality driver input data for EFlows assessments is obtained through five key steps as described below.

Step 1: Preparation of hydrological simulations

The application of the physical state approach to EFlows requires **long-term river inflow patterns**, for example, using 70-100 year simulated monthly flows (Table 4.3).

Step 2: Homogenous zonation in estuaries

When applying the physical state approach to a specific estuary, it is often not realistic to present the estuary as a single 'zone', especially in larger systems that display strong salinity gradients (e.g. Open: full gradient states). To overcome this challenge, an estuary can be sub-divided into representative homogenous zones, as illustrated in Figure 4.2, collapsing complex physical and chemical processes that occur at a range of spatial scales to simplified zonation in a manner that is useful for ecological and socio-economic response interpretation (van Niekerk *et al.* 2019a).

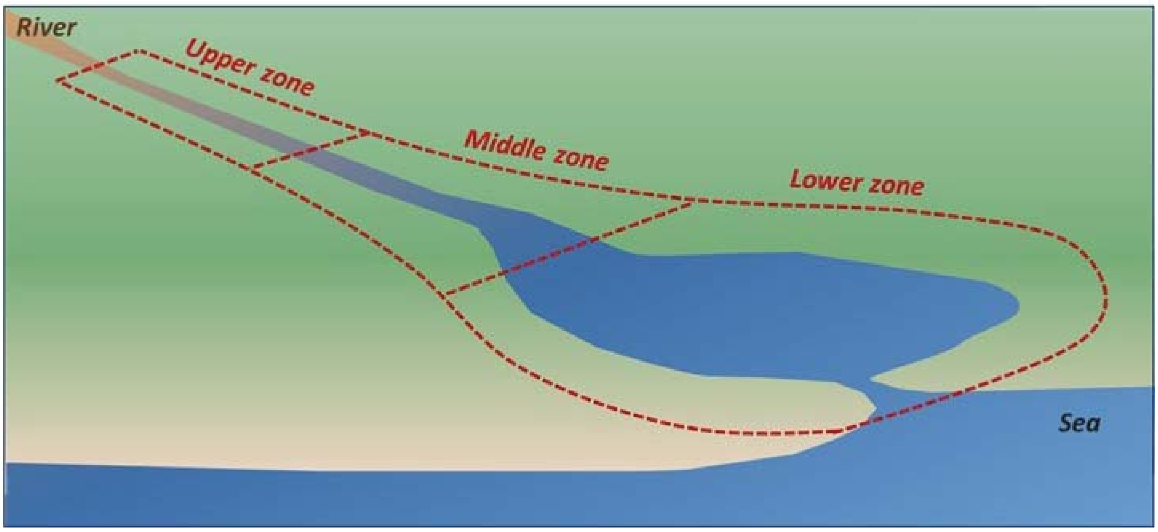


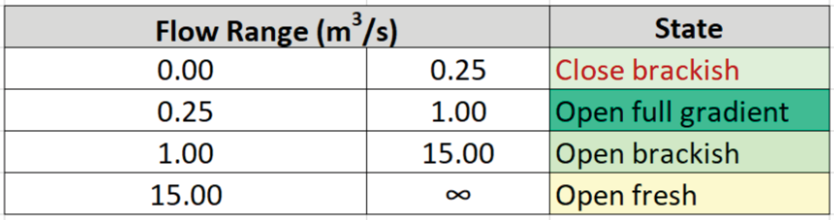
Figure 4.2 **Conceptualising longitudinal zoning in application of abiotic state approach in EFlows studies (Source: van Niekerk *et al.* 2023a)**

The homogenous zones are usually demarcated conceptually, using for example bathymetry, dominant mixing processes, degree of stratification, and homogeneity in water residency periods. The occurrence of key habitats and/or species can also be considered in the selection of representative zones, especially where their occurrence may be influenced by water quality (van Niekerk *et al.* 2019a; Taljaard *et al.* 2022).

Step 3: Defining abiotic states and characteristic flow ranges

While it is possible to identify generic physical states typically associated with an estuarine ecosystem type, largely based on the functional types (Figure 4.1), the flow ranges associated with each of these states are site-specific and largely dependent on the size and shape of the estuary, hydrological inputs, tidal regime and the degree of connectivity to the estuary. Using a River dominated estuary as an example, which typically comprises four states, namely Closed: brackish, Open: full gradient, Open: fresh/brackish and Open: fresh. The typical flow ranges associated with each of these states is estuary specific. Depending on the availability of data and resources, flow-state relationships can be derived from long-term measurements of inflow and salinity patterns in an estuary, derived using numerical modelling tools, extrapolated from data on a similar estuary functional type, or using expert judgement (outputs must be labelled to be of low confidence where calibration information is limited). Table 4.7 provides hypothetical flow ranges associated with the typical state for a River dominated estuary.

Table 4.7 Illustration of flow range allocations to typical physical states for a River dominated estuary (Source: Van Niekerk *et al.* 2023a)

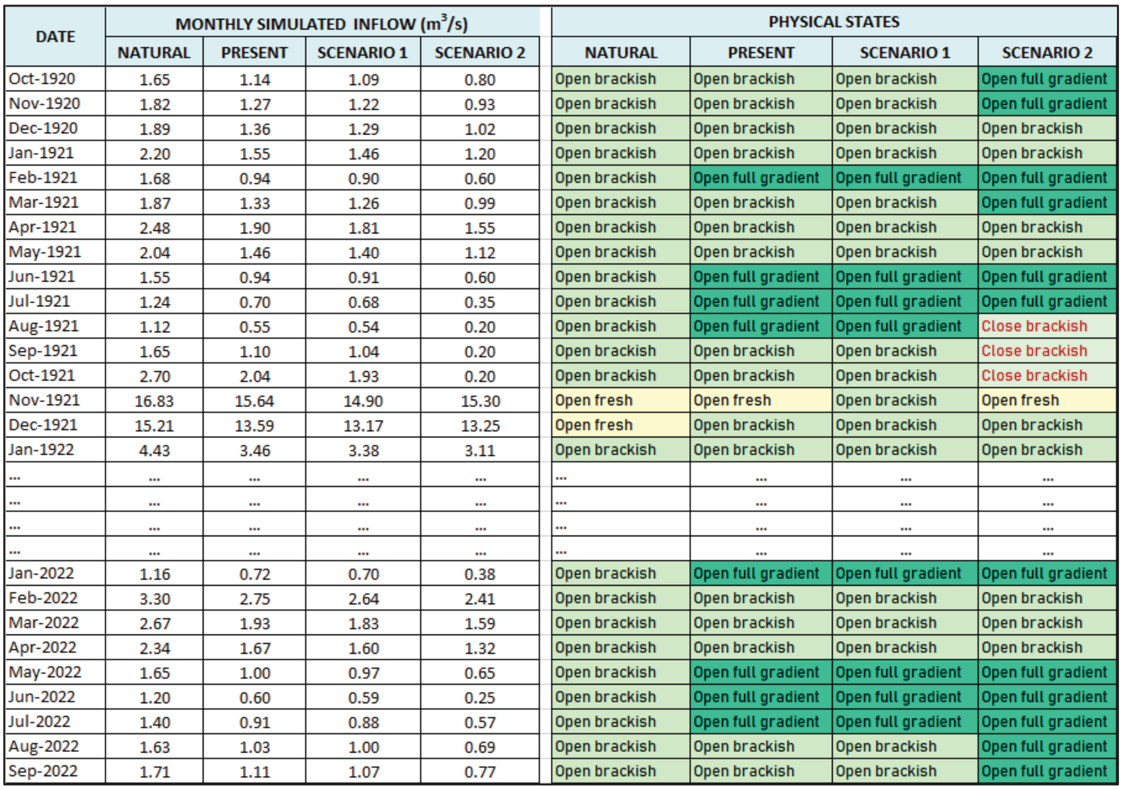


Flow Range (m^3/s)		State
0.00	0.25	Close brackish
0.25	1.00	Open full gradient
1.00	15.00	Open brackish
15.00	∞	Open fresh

With flow ranges allocated to relevant physical states, it is then possible to ‘translate’ monthly flow patterns into ‘physical state patterns, as illustrated in Table 4.8.

Physical states, therefore, provide a means of collapsing complex temporal scales to simpler scales that are more accessible for ecological and socio-economic interpretation (Taljaard *et al.* 2022; van Niekerk *et al.* 2019a).

Table 4.8 **Translating simulated monthly flows into typical monthly physical states for the simulated period using allocated flow ranges (Source: Van Niekerk *et al.* 2023a)**

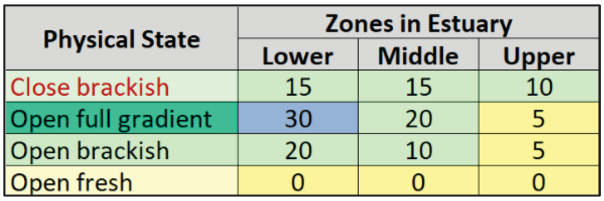


DATE	MONTHLY SIMULATED INFLOW (m^3/s)				PHYSICAL STATES			
	NATURAL	PRESENT	SCENARIO 1	SCENARIO 2	NATURAL	PRESENT	SCENARIO 1	SCENARIO 2
Oct-1920	1.65	1.14	1.09	0.80	Open brackish	Open brackish	Open brackish	Open full gradient
Nov-1920	1.82	1.27	1.22	0.93	Open brackish	Open brackish	Open brackish	Open full gradient
Dec-1920	1.89	1.36	1.29	1.02	Open brackish	Open brackish	Open brackish	Open brackish
Jan-1921	2.20	1.55	1.46	1.20	Open brackish	Open brackish	Open brackish	Open brackish
Feb-1921	1.68	0.94	0.90	0.60	Open brackish	Open full gradient	Open full gradient	Open full gradient
Mar-1921	1.87	1.33	1.26	0.99	Open brackish	Open brackish	Open brackish	Open full gradient
Apr-1921	2.48	1.90	1.81	1.55	Open brackish	Open brackish	Open brackish	Open brackish
May-1921	2.04	1.46	1.40	1.12	Open brackish	Open brackish	Open brackish	Open brackish
Jun-1921	1.55	0.94	0.91	0.60	Open brackish	Open full gradient	Open full gradient	Open full gradient
Jul-1921	1.24	0.70	0.68	0.35	Open brackish	Open full gradient	Open full gradient	Open full gradient
Aug-1921	1.12	0.55	0.54	0.20	Open brackish	Open full gradient	Open full gradient	Close brackish
Sep-1921	1.65	1.10	1.04	0.20	Open brackish	Open brackish	Open brackish	Close brackish
Oct-1921	2.70	2.04	1.93	0.20	Open brackish	Open brackish	Open brackish	Close brackish
Nov-1921	16.83	15.64	14.90	15.30	Open fresh	Open fresh	Open brackish	Open fresh
Dec-1921	15.21	13.59	13.17	13.25	Open fresh	Open brackish	Open brackish	Open brackish
Jan-1922	4.43	3.46	3.38	3.11	Open brackish	Open brackish	Open brackish	Open brackish
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
Jan-2022	1.16	0.72	0.70	0.38	Open brackish	Open full gradient	Open full gradient	Open full gradient
Feb-2022	3.30	2.75	2.64	2.41	Open brackish	Open brackish	Open brackish	Open brackish
Mar-2022	2.67	1.93	1.83	1.59	Open brackish	Open brackish	Open brackish	Open brackish
Apr-2022	2.34	1.67	1.60	1.32	Open brackish	Open brackish	Open brackish	Open brackish
May-2022	1.65	1.00	0.97	0.65	Open brackish	Open full gradient	Open full gradient	Open full gradient
Jun-2022	1.20	0.60	0.59	0.25	Open brackish	Open full gradient	Open full gradient	Open full gradient
Jul-2022	1.40	0.91	0.88	0.57	Open brackish	Open full gradient	Open full gradient	Open full gradient
Aug-2022	1.63	1.03	1.00	0.69	Open brackish	Open brackish	Open brackish	Open full gradient
Sep-2022	1.71	1.11	1.07	0.77	Open brackish	Open brackish	Open brackish	Open full gradient

Step 4a: Derive salinity matrices across states and zones

Taljaard *et al.* (2022) provided a method to quantify salinity change, using simulated monthly physical states combined with longitudinal estuary zoning (Table 4.9). Ideally, the matrix should be derived from representative salinity data sets collected different flow regimes (or physical states) characteristics of the studied estuary, but in data-limiting environments such data may not always be readily available in which case it needs to be derived from alternative sources. For example, numerical modelling technologies can be used to simulate salinity distribution under representative different flow ranges. Alternative, available data from comparable systems of similar ecosystem type and dimensions could be interrogated and adapted for the studies estuary based on expert judgement (Taljaard *et al.* 2022).

Table 4.9 **Construct of salinity matrices for typical physical states and across estuary zones (Source: Van Niekerk *et al.* 2023a)**



Physical State	Zones in Estuary		
	Lower	Middle	Upper
Close brackish	15	15	10
Open full gradient	30	20	5
Open brackish	20	10	5
Open fresh	0	0	0

Step 4b: Derive water quality matrices across states and zones

It is necessary to first develop matrices for salinity, as these provide insight into salinity regimes and are a proxy for the conservative mixing process in estuaries. This step involves the building of a matrix allocating representative salinity properties to various zones in an estuary under each of the identified physical states (Table 4.10).

Like the salinity matrix, matrices also need to be developed for various biogeochemical properties under investigation, including dissolved oxygen, pH, turbidity, and in organic nutrients. Biogeochemical (or water quality) matrices ideally also should be derived from representative data sets collected under different flow regimes (or physical states) characteristics of the studied estuary (Table 4.10).

Table 4.10 Construct of water quality matrices for typical physical states and across estuary zones (Source: Van Niekerk et al. 2023a)

Dissolved inorganic nitrogen (μg/ℓ)	**NATURAL**			**PRESENT**		
Physical State	**Zones in Estuary**			**Zones in Estuary**		
	Lower	**Middle**	**Upper**	**Lower**	**Middle**	**Upper**
Close brackish	20	20	20	100	100	100
Open full gradient	30	20	10	50	100	200
Open brackish	20	20	50	100	100	200
Open fresh	10	10	10	100	100	200
Dissolved Oxygen	**NATURAL**			**PRESENT**		
Physical State	**Zones in Estuary**			**Zones in Estuary**		
	Lower	**Middle**	**Upper**	**Lower**	**Middle**	**Upper**
Close brackish	7	7	8	6	6	6
Open full gradient	7	7	8	7	6	6
Open brackish	7	7	8	7	6	6
Open fresh	8	8	8	8	8	8
Turbidity (NTU)	**NATURAL**			**PRESENT**		
Physical State	**Zones in Estuary**			**Zones in Estuary**		
	Lower	**Middle**	**Upper**	**Lower**	**Middle**	**Upper**
Close brackish	5	5	5	10	10	10
Open full gradient	5	5	5	10	10	10
Open brackish	5	5	5	10	15	20
Open fresh	10	10	10	50	50	50

However, in data-limited environments, it is unlikely that water quality would have been sampled to such as comprehensive extent, again requiring alternative approaches for the population of such matrices that can range from sophisticated numerical models (e.g. Duvail and Hamerlynk 2003; Van Ballegooyen *et al.* 2004; Ben-Hamadou *et al.* 2011; Peñas *et al.* 2013; Acreman *et al.* 2014a&b) to expert judgment. In instances where data and numerical resources are lacking, salinity-property plots can be used to estimate zonal biogeochemical characteristics, derived from water quality properties of the end sources (freshwater inflow [salinity ~0] and seawater [salinity ~35]). This approach works most effectively where low retention efficiency is expected and physical mixing is the dominant process determining in situ water quality concentrations (e.g. in open states of relatively linear ecosystem types, such as River dominated and predominantly open estuaries). Calculation of zonal water quality concentrations, using zonal salinity and concentrations in source waters can be calculated as follows:

$$\text{Conc. in zone } = \left(\frac{35 - \text{Salinity in zone}}{35} \times \text{Conc. Inflow at head of estuary}\right) + \left(\frac{1}{35 - \text{Salinity in zone}} \times \text{Conc. in sea}\right)$$

Nuances in the application of salinity-property approach, e.g. inclusion of effluent inflows and flow entering along the length are an estuary, are discussed in greater detail by Taljaard et al. (2022). In systems with relatively low retention efficiencies, that are not eutrophic, oxygen saturation tables (matching saturated oxygen concentrations to salinity and temperature) can be used to estimate zonal dissolved oxygen characteristics.

However, salinity-property plots, can become problematic in estuarine ecosystem types that are more circular and in closed states (e.g. Estuarine lakes and intermittently closed estuaries), where longer water column retention when the influence of in situ biochemical and biological processes (e.g. primary production and remineralisation) can become more dominant compared with better flushed, open states). In those instances, zonal water quality characteristics can best be derived from place-based measured or modelled data. Alternatively in data-limiting environments, characteristics can be estimated using experiential knowledge and ‘pattern matching’ with other, comparable estuarine ecosystems, but then assumptions applied in the construct of the matrices must be explicitly communicated (Taljaard *et al.* 2022).

In the case of water quality, it is often the case that present biogeochemical characteristics differ from that of the natural state owing to anthropogenic enrichment of nutrients and turbidity, with ripple effects into other system's biogeochemical properties such as dissolved oxygen and pH. In such instances, matrices need to be developed for both natural and present (also possible future scenarios where changes in water quality in inflow are expected). Historical data that precedes human development usually are not available. Therefore, the construct of matrices for natural conditions is best derived from published literature on other (near-natural) systems of the same ecosystem type and mouth behaviour, as well as similar catchment geology and vegetation characteristics, and oceanic conditions. Salinity-property plots, using expected natural concentration in water sources for states representing low retention efficiencies (Taljaard *et al.* 2022).

Step 5: Calculate time series salinity and water quality input data

Using simulated flow data sets and the matrices, it is then possible to calculate monthly zonal time series data for biogeochemical driver indicators as illustrated in Table 4.3. By first translating simulated monthly flows (over 70 to 100-year periods) into monthly physical state distribution (Table 4.11), and then estimating monthly zonal distribution patterns, provide a means of collapsing complex temporal and spatial scales of physical and biogeochemical processes to simpler scales that are more accessible for ecological and socio-economic interpretation (Taljaard *et al.* 2022; van

Table 4.11 **Calculation of physical and water quality distribution patterns across various zones and physical states, using matrices (Source: Van Niekerk *et al.* 2023a)**

DATE	SIMULATED INFLOW (m^3/s)	PHYSICAL STATE	SALINITY			DIN (mg/ℓ)			DISSOLVED OXYGEN (mg/ℓ)			TURBIDITY (NTU)		
			Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper	Lower	Middle	Upper
Oct-1920	1.14	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Nov-1920	1.27	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Dec-1920	1.36	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Jan-1921	1.55	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Feb-1921	0.94	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Mar-1921	1.33	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Apr-1921	1.90	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
May-1921	1.46	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Jun-1921	0.94	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Jul-1921	0.70	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Aug-1921	0.55	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Sep-1921	1.10	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Oct-1921	2.04	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Nov-1921	15.64	Open fresh	0	0	0	100	100	100	6.0	6.0	6.0	10	10	10
Dec-1921	13.59	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Jan-1922	3.46	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Jan-2022	0.72	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Feb-2022	2.75	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Mar-2022	1.93	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Apr-2022	1.67	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
May-2022	1.00	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Jun-2022	0.60	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Jul-2022	0.91	Open full gradient	30	20	5	100	100	100	6.0	6.0	6.0	10	10	10
Aug-2022	1.03	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10
Sep-2022	1.11	Open brackish	20	10	5	100	100	100	6.0	6.0	6.0	10	10	10

Niekerk *et al.* 2019), especially in data-limiting environments where resources to execute comprehensive data collection programmes or to apply expensive, sophisticated numerical modelling tools are mostly not available.

This step can be executed through simple spreadsheet models, using look-up tables (e.g. Index function in MS Excel). Important is that the confidence of model outputs is heavily dependent on the extent and accuracy of input data, but because the method requires transparency on input assumptions it can be challenged and refined as more data becomes available and understanding improves (Taljaard *et al.* 2022).

4.1.3 Sediment load

A catchment is characterized by its climate, size, geology, slope, vegetation and land-use practices, which in turn determine the character of sediments transported down the rivers and discharged into the coast (e.g. predominantly fine or medium-grained) (Stein *et al.* 2021). For instance, rivers that primarily drain coarse-grained rocks resistant to erosion will have low sediment yields comprised of medium to coarse-grained material. The delivery, deposition and erosion of sediments in estuaries shape their geomorphology. Freshwater inflows transport sediment particulate material to estuaries, which then settle out in areas of low velocity. Settling rates can be enhanced by flocculation associated with increasing salinity (Chilton *et al.* 2021). Sediment delivery is important for building habitat structures in estuaries. Turbulent wave action in the coastal surf zone can also re-suspends sediments, which are then transported by flood tides and deposited in the mouths of estuaries, forming sand bars.

Generally, sediment input from the catchment is divided into coarse (sand) and fine (silt) material (Table 4.12):

- Silt (Sediment input/load)
- Sand (Sediment input/load)

Table 4.12 Characterisation and relevance of selected sediment 'driver' indicators

DRIVER INDICATOR	DESCRIPTION AND MOTIVATION
Silt (sediment input/load)	Silt is largely transported as suspended load. Normally the main source of silt during flood events is catchment erosion processes. This can be enhanced through local bed and bank disturbance through land-use change in the catchment and surrounding environs. Although most sediment is transported during higher flows, as a general principle, there is a positive but variable relationship between suspended sediment concentration and flow discharge. Once in suspension, most silt will be transported through the channel as a load; significant deposition only occurs in low-velocity areas.
Sand (sediment input/load)	Sand is carried both in suspension and as bed load. The load will determine the potential for sand deposition in an estuary or floodplain. Sand is likely to be deposited at the end of a high-flow event. Sand is episodically supplied to the channel from the catchment but is also transported down the channel in a "jerky conveyor belt" as sand deposits on the bed are remobilized.

Using a combination of measured and modelled data a catchment-specific relationship can be developed that relates the river flows to sediment load (e.g. Figure 4.3). This relationship in turn can then be linked to the simulated hydrology to provide a measure of the expected sediment load at the head of the estuary.

Alternatively, these indicators can be incorporated from the river assessment as an input into the estuary (see descriptions and response curves for Clay and silt, sand indicators in sections 3.3.1 and 3.3.2)

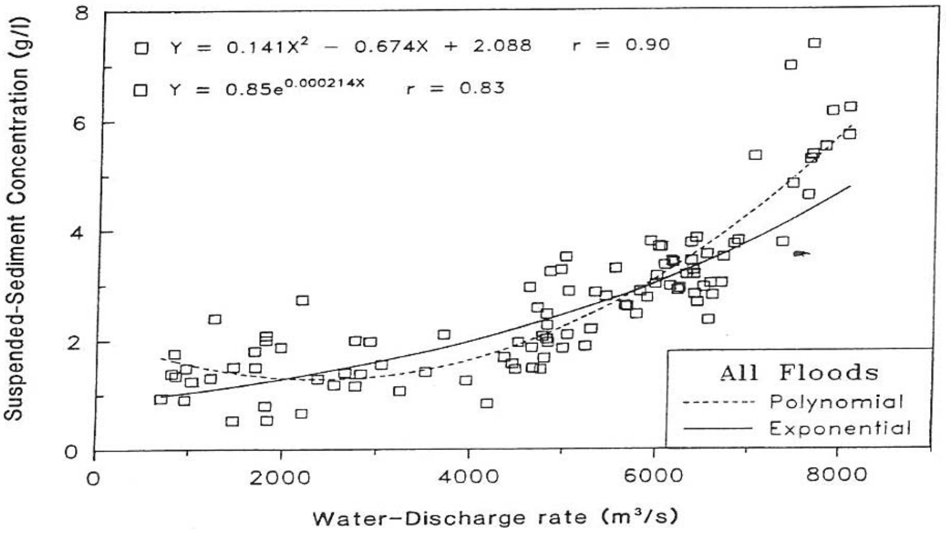


Figure 4.3 **Example of the relationship between suspended-sediment concentration and freshwater flow for a fluvially-dominated estuary (Source: Bremner *et al.* 1990)**

4.2 Hydrodynamics

Drawing on the experience gained through the application of EFlows assessments using the South African method (DWAF 2008), the following are considered the most relevant Hydrodynamic indicators:

- Marine connectivity
- Water levels/Tidal amplitude
- Water retention
- Floodplain inundation
- Flow velocity.

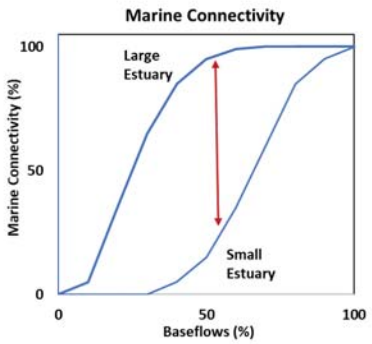
Using measured, modelled or literature the relationship between river inflow and marine connectivity can be established. Typically, river inflow and observational data/water level recorded data spanning 10 to 20 closures are needed to determine the flow range an estuary can close at under normal conditions. In the absence of measured data, a ‘water balance’ approach can be used to calculate the volume of water (derive from the open water extent) that is needed over a set period to fill the estuary and breach it. Similarly, using measured, modelled or literature the relationship between river inflow and the water levels in the various zones of the estuary can also be derived and depicted in a coupled flow-water level relationship that can be utilised in an EFlows assessment. Water retention is a site-specific indicator and needs to be numerically calculated (in the case of small closed estuaries) or modelled to determine the relationship between river inflow and water retention in the various zones of the estuary. While floodplain inundation needs to be simulated using numerical modelling tools to provide an accurate indication of the extent the floodplain is inundated under different flood regimes. This information in turn can be simplified to indicate the extent of inundation in each zone of the estuary in response to different flow ranges. This information can be collapsed into the physical states to some degree, but often a separate flow-floodplain inundation relationship is developed using flood volumes/size as a driver for the indicator. Topo-bathymetric data and water levels at different locations along the estuary are needed to calculate discharges and cross-sectional averaged flow velocities resulting in this parameter seldom being incorporated in desktop studies (no field observations or modelling).

4.2.1 Marine connectivity

The sensitivity of an estuary mouth to closure can roughly be correlated to the river inflow, particularly during low flow periods, required to keep the mouth open. For many estuaries, especially the smaller ones, the most important factor in keeping the mouth open is river flow, and particularly base flows. In addition to river flow there are also other factors and/or a combination of thereof, that may contribute to an estuary’s sensitivity to mouth closure.

Typically, larger estuaries are less sensitive to mouth closure than smaller estuaries, because of larger catchment flows and greater tidal flows through the mouth that enhance river flow (Table 4.13). Small estuaries are very sensitive to flow reduction as this is the main force keeping the mouth open, once flow decrease below a certain volume the system will close, and remain closed, until such time as flow increase enough to cause a mouth breaching. The more sediment available in the adjacent marine environment, the greater is the chance of mouth closure. In estuaries where there is not a large amount of sediment available, for example on a rocky coastline or where longshore transport is further offshore, the system would be less sensitive to flow reductions. The stronger the wave action in the mouth, the greater is the likelihood of mouth closure. Wave conditions in the mouth are often influenced by the degree of protection of the mouth, e.g. by a headland, and beach slope. A steep beach slope normally means that high-energy wave action occurs on the beach at the mouth, resulting in higher suspended sediment load. A mild beach slope means that less energetic wave action occurs at the mouth and thus provides some protection against wave action. The timing, frequency and duration of mouth closure strongly affect abiotic habitats and biological communities found in estuaries.

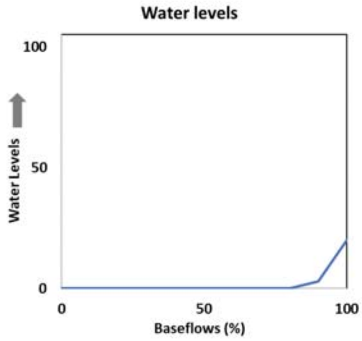
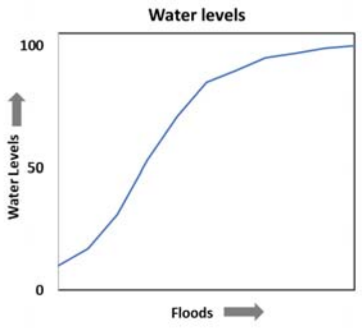
Table 4.13 Marine Connectivity links and explanations

MARINE CONNECTIVITY	
Link and response curve	**Explanation**
	Base flow: There is a positive relationship between baseflows and marine connectivity. The higher the baseflows the less likely the estuary is to be closed to the sea.

4.2.2 Water levels/Tidal amplitude

The water level variability in estuaries, especially in meso and macrotidal systems, has forcing mechanisms that affect both the magnitude and temporal characteristics of the water level variability (Table 4.14). This could include freshwater (fluvial) inflows into the systems, tidal forcing as well as other oceanic influences such as storm surges and wave set-up. Changes in the tidal amplitude are an indicator of channel erosion or deposition. Changes in water levels can thus be the result of flow changes, increased catchment erosion, dredging or infrastructure development (bridges/jetties). Sea level rise also poses a threat to many estuaries. In closed systems, an increase/decrease in rainfall and associated runoff will result in a related increase/decrease in water levels driven by catchment inputs and direct rainfall on estuary surface areas. When an estuary mouth is closed the inflowing freshwater from a river, or groundwater, gradually fills the system (on condition that inflow exceeds evaporation and seepage losses). Under natural conditions, the water levels in the estuary would eventually exceed the height of the berm and a breaching would occur at levels. During a natural breaching, the maximum water level in an estuary is reached when the outflow through the mouth exceeds the river inflow. In estuaries, the spatial and temporal variation of physicochemical and biological parameters is strongly influenced by water levels and/or tidal dynamics. Changes in water levels can result in a shift in the distribution of macrophyte habitats (e.g. mangrove species) or the ultimate loss of habitats. In addition, water level fluctuations drive access to food and shelter in intertidal and subtidal areas. For example, water levels affect depth, area of inundation, wetted perimeter, and vegetation; and therefore is a determinant of fish habitat.

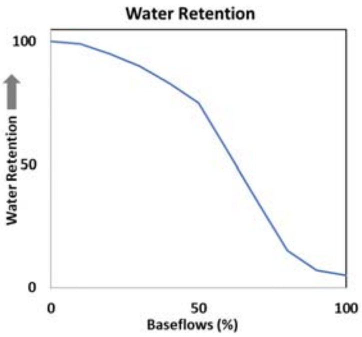
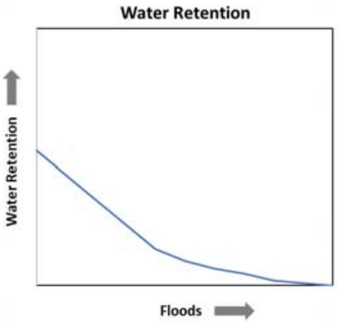
Table 4.14 Water levels / Tidal amplitude links and explanations

WATER LEVELS / TIDAL AMPLITUDE	
Link and response curve	**Explanation**
	Baseflows: While tidal flows generally dominate water levels in open estuaries, an increase in baseflows of larger catchments can result in an increase in water levels, especially in the upper reaches where tidal flow are lower. The greater the magnitude of the flows, the higher the water level. However, the impact is much lower than flood level flows. If baseflows are severely reduced in smaller temporarily open/closed estuaries, mouth closure can occur increasing water levels which would result in an inverse relationship based on site specific information.
	Floods: Floods play a key role in water levels, the greater the magnitude of the flood, the higher the water level.

4.2.3 *Water retention*

The residence time of water in an estuary (inversely related to the flushing rate) is strongly influenced by freshwater and tidal flows (Table 4.15). Retention in turn affects the distribution of salinity, processing times of nutrients, dissolved oxygen and turbidity, sedimentation rates of particulates, contaminants and pathogens, and contaminant exposure risk to resident organisms. Residence time can be highly variable across a range of time scales, from inter-annual to tidal, and modified by estuarine morphology (Chilton *et al.* 2021). While tidal flows are generally a constant over neap-spring cycles in permanently open estuaries, a decrease in river flow results in an increase in residence time, often increasing an estuary's sensitivity to nutrient enrichment. Anthropogenic actions such as dredging and port construction can increase flushing by the sea under tidal action.

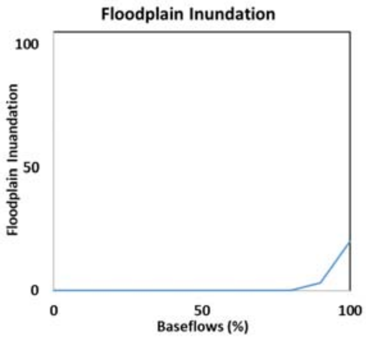
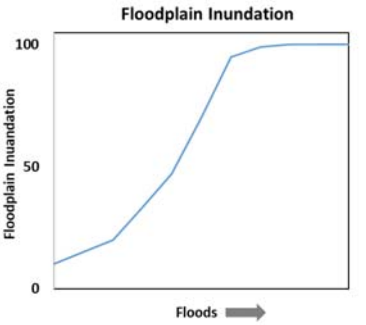
Table 4.15 Water retention links and explanations

WATER RETENTION	
Link and response curve	**Explanation**
	Baseflows: Although, tidal exchange normally dominates estuaries under low flow conditions, if baseflows are severely reduced, retention increases (especially if mouth closure occurs) depending on the flow range.
	Floods: Water retention is negatively influenced by floods and can be reduced to days or even hours during large events.

4.2.4 Floodplain inundation

Floodplain inundation occurs during freshets and floods (Table 4.16). During large events, floods can deposit rich, fertile alluvium on estuarine floodplains. Inundation of the floodplains also helps recharge the groundwater and reduce soil salinities. Estuarine floodplains and wetlands are important for breeding, nursery, and feeding grounds for marine fisheries and coastal floodplains are important to waterfowl and other wildlife. Estuarine vegetation, such as reeds benefit from floodplain inundation and expand, colonizing the newly inundated areas. Because of their high tolerance to inundation, they can outcompete other terrestrial species. If the floodplain is less frequently inundated, the vegetation extent will decrease as they need wet habitat to grow.

Table 4.16 Floodplain inundation links, explanations and supporting literature

FLOODPLAIN INUNDATION	
Link and response curve	**Explanation and supporting literature**
	Baseflows: In open estuaries baseflows play a minor role in water levels and floodplain inundation; the greater the magnitude of the flow, the higher the water level and the more of the floodplain is inundated. The impact is lower than flood flows.
	Floods: Floods play a key role in water levels and floodplain inundation; the greater the magnitude of the flood, the higher the water level and the more of the floodplain is inundated.

4.3 Physical habitat extent (geomorphology)

The description of the sediment processes in an estuary primarily characterises the physical and structural habitat. This is achieved through an evaluation of the distribution of sediments in terms of sandy/muddiness and organic content, as well as the major factors influencing the subtidal, intertidal, supratidal and/or floodplain areas. Disturbance of the sediment erosion/deposition equilibrium in an estuary can lead to siltation, resulting in the estuary becoming shallower, or it can lead to the erosion of important estuarine habitats.

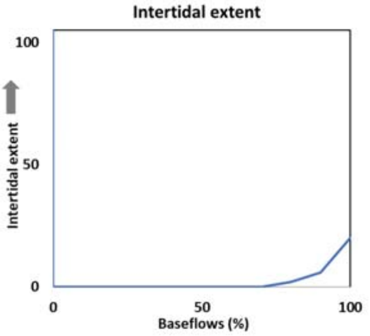
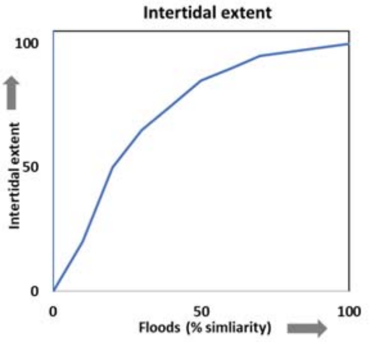
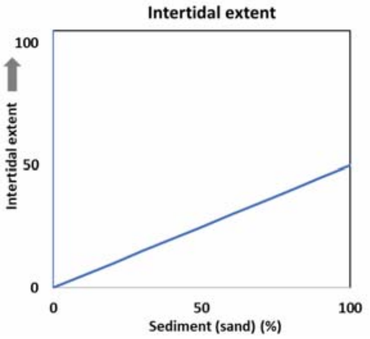
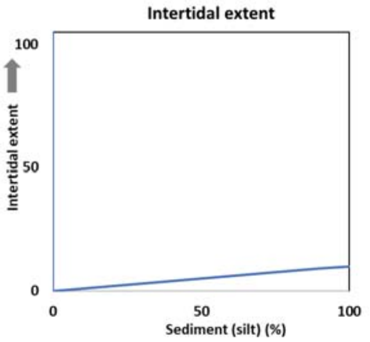
Drawing on the experience gained through the application of EFlows assessments using the South African method (DWAF 2008), the following are considered the most relevant indicators:

- Intertidal extent
- Supra tidal extent
- Subtidal volume/extent
- Sediment structure/grain size.

4.3.1 Intertidal extent

Intertidal habitats are found between the high tide and low tide, experiencing fluctuating influences of land and sea (Table 4.17). Intertidal ecosystems are a dynamic complex of plant, animal and micro-organism communities and their non-living environment that interact as a functioning unit, and are regularly exposed at low tides (e.g. mangroves or saltmarsh on muddy substrate). This indicator is dependent on the river inflow, mouth state, and the sediment load coming from the catchment and should be linked to upstream river sand and mud/silt predicted load.

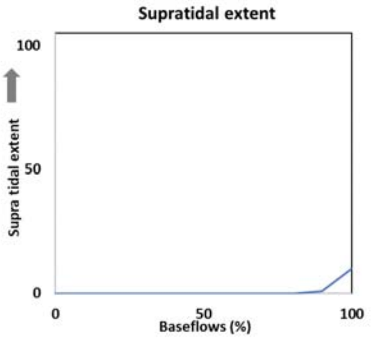
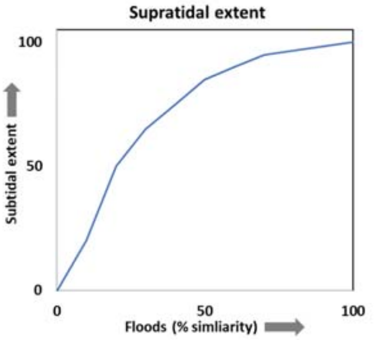
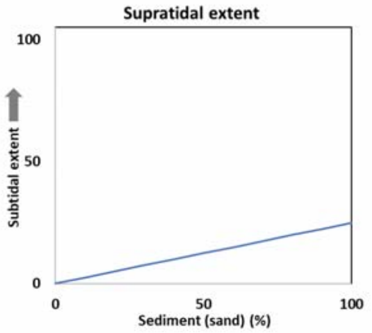
Table 4.17 Intertidal extent links and explanations

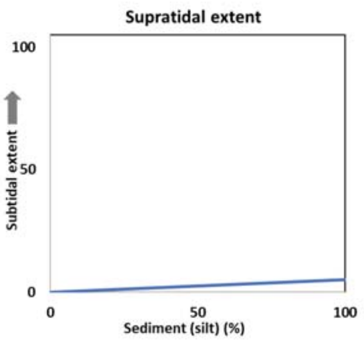
INTERTIDAL EXTENT	
Link and response curve	**Explanation**
	Typically baseflow, as a result of lower velocities, doesn't transport significant volumes of sediment into, or through, an estuary. However, during lower flow periods, sediment that is normally transported through an estuary may settle out in the upper reaches and/or more marine sediment may enter on a high tide than leave the system on the low tide.
	Episodic floods play a key role in the long-term erosion – deposition equilibrium of estuaries, with large events (>1:20 year return period) scouring significant volumes of both catchment and marine-derived sediments during such events. Large floods also replenish floodplain sediments and can result in the scouring and formation of structures such as islands, shoals, and backwater areas. Floods also play a critical role in the removal of accumulated organic matter from estuaries.
	Sand is carried both in suspension and bed load. The load will determine the potential for sand deposition in an estuary. Sand is likely to be deposited at the end of a high-flow event. Sand is episodically supplied to the channel from the catchment but is also transported down the channel in a "jerky conveyor belt" as sand deposits on the bed are remobilized. This driver is normally incorporated from the river assessment as an input into the estuary
	Silt is largely transported as suspended load. Normally the main source of silt during flood events is catchment erosion processes. This can be enhanced through local bed and bank disturbance through land-use change in the catchment and surrounding environs. As a general principle, there is a positive but variable relationship between suspended sediment concentration and flow discharge. Although most sediment is transported during higher flows. Once in suspension, most silt will be transported through the channel as a load; significant deposition only occurs in low-velocity areas. This driver is normally incorporated from the river assessment as an input into the estuary.

4.3.2 Supra tidal extent

That part of the estuarine floodplain is located above the high tide that extends into higher lands. These areas are only inundated under spring tides and during floods (Table 4.18). Supratidal areas are important refugia during floods. This indicator is dependent on the flood size/volume, mouth state, and the sediment load coming from the catchment and should be linked to upstream river sand and mud/silt predicted load.

Table 4.18 Supra tidal extent links and explanations

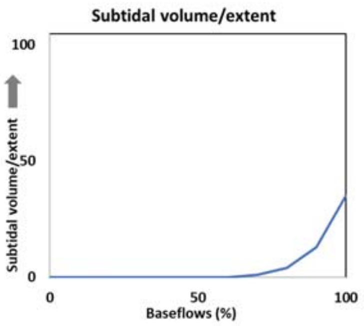
SUPRA TIDAL EXTENT	
Link and response curve	**Explanation**
	Baseflows: Typically baseflow, as a result of lower velocities, doesn't transport significant volumes of sediment into, or through, an estuary. However, during lower flow periods, sediment that is normally transported through an estuary may settle out in the upper reaches and/or more marine sediment may enter on a high tide than leave the system on the low tide. Supratidal sediment processes will only be impacted at the higher end of the flow duration curve.
	Floods: Episodic floods play a key role in the long-term erosion – deposition equilibrium of estuaries, with large events (>1:20 year return period) scouring significant volumes of both catchment and marine-derived sediments during such events. Large floods also replenish floodplain sediments and can result in the scouring and formation of structures such as islands, shoals, and backwater areas. Floods also play a critical role in the removal of accumulated organic matter from estuaries.
	Sand: Sand is carried both in suspension and bed load. The load will determine the potential for sand deposition in an estuary or floodplain. Sand is likely to be deposited at the end of a high-flow event. Sand is episodically supplied to the channel from the catchment but is also transported down the channel in a "jerky conveyor belt" as sand deposits on the bed are remobilized. This driver is normally incorporated from the river assessment as an input into the estuary

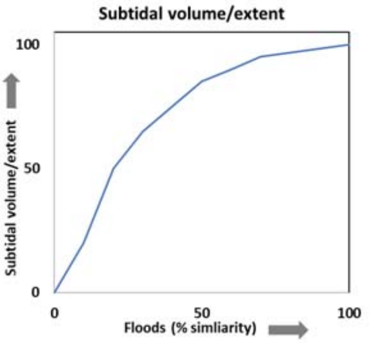
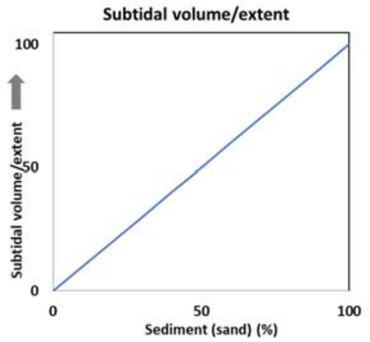
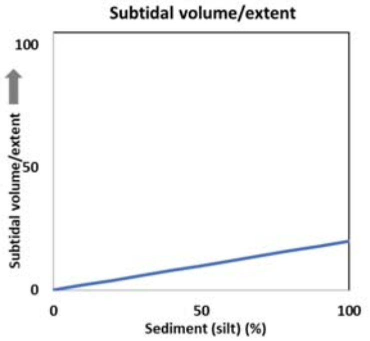
SUPRA TIDAL EXTENT	
Link and response curve	**Explanation**
	Silt: Silt is largely transported as suspended load. Normally the main source of silt during flood events is catchment erosion processes. This can be enhanced through local bed and bank disturbance through land-use change in the catchment and surrounding environs. As a general principle, there is a positive but variable relationship between suspended sediment concentration and flow discharge. Although most sediment is transported during higher flows. Once in suspension, most silt will be transported through the channel as a load; significant deposition only occurs in low-velocity areas. This driver is normally incorporated from the river assessment as an input into the estuary.

4.3.3 Subtidal volume/extent

The size and shape of an estuary determines its inherited physical features – tidal variation, retention time, responsiveness to flow and structural habitat features such as inter- and supratidal area (Table 4.19). The disturbance of the sediment erosion or deposition equilibrium in an estuary can lead to siltation, resulting in the estuary becoming shallower, or it can lead to the erosion of important estuarine habitats. Under natural conditions, estuaries are in a long-term erosion or deposition equilibrium. However, this equilibrium can be disturbed because of changes in flow, especially if the occurrences and magnitudes of major floods are changed. This indicator is largely dependent on the sediment load coming from the catchment and should be linked to upstream river sand and mud/silt predicted load.

Table 4.19 Subtidal volume/extent links and explanations

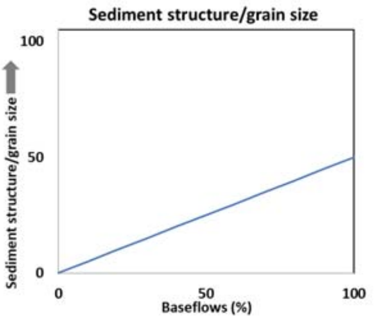
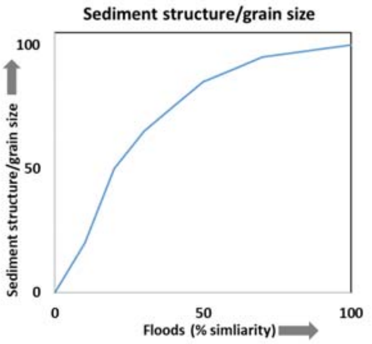
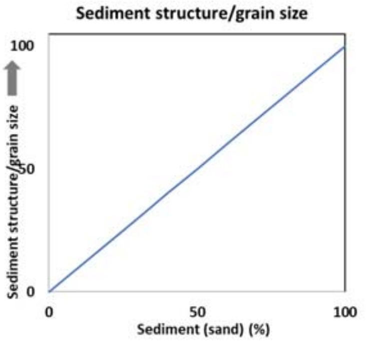
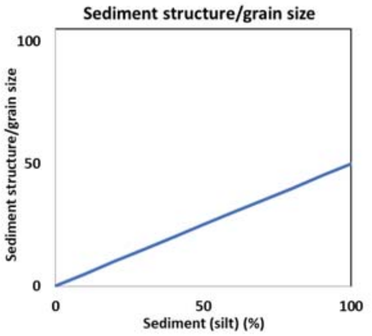
SUBTIDAL VOLUME/EXTENT	
Link and response curve	**Explanation**
	Baseflows: Typically baseflow, as a result of lower velocities, don't transport significant volumes of sediment into, or through, an estuary. However, during lower flow periods, sediment that is normally transported through an estuary may settle out in the upper reaches and/or more marine sediment may enter on a high tide than leaves the system on the low tide.

SUBTIDAL VOLUME/EXTENT	
Link and response curve	**Explanation**
	Floods: Episodic floods play a key role in the long-term erosion – deposition equilibrium of estuaries, with large events (>1:20 year return period) scouring significant volumes of both catchment and marine-derived sediments during such events. Large floods also replenish floodplain sediments and can result in the scouring and formation of structures such as islands, shoals, and backwater areas. Floods also play a critical role in the removal of accumulated organic matter from estuaries.
	Sand: Sand is carried both in suspension and bed load. The load will determine the potential for sand deposition in an estuary or floodplain. Sand is likely to be deposited at the end of a high-flow event. Sand is episodically supplied to the channel from the catchment but is also transported down the channel in a "jerky conveyor belt" as sand deposits on the bed are remobilized. This driver is normally incorporated from the river assessment as an input into the estuary
	Silt: Silt is largely transported as suspended load. Normally the main source of silt during flood events is catchment erosion processes. This can be enhanced through local bed and bank disturbance through land-use change in the catchment and surrounding environs. As a general principle, there is a positive but variable relationship between suspended sediment concentration and flow discharge. Although most sediment is transported during higher flows. Once in suspension, most silt will be transported through the channel as a load; significant deposition only occurs in low-velocity areas. This driver is normally incorporated from the river assessment as an input into the estuary.

4.3.4 Sediment structure/grain size

Change in the flood regime or volume of sediment entering the estuary can reflect as changes in the grain size fractions and resultant changes in biotic habitats. For example, the deposition of fine-grained particles allows for colonisation by plants (e.g. saltmarsh, mangroves) and infauna (e.g. polychaetes). In addition, freshwater flow interacts with marine sediments at the mouth of estuaries (Chilton *et al.* 2021). Individual faunal species preferences are highly variable and often related to preferred food sources. The burying ability and crypsis of some species are governed by sediment characteristics (Table 4.20).

Table 4.20 Sediment structure/grain size links and explanations

SEDIMENT STRUCTURE/GRAIN SIZE	
Link and response curve	**Explanation**
	Typically, baseflow, as a result of lower velocities, doesn't transport significant volumes of sediment into, or through, an estuary. However, during lower flow periods, sediment that is normally transported through an estuary may settle out in the upper reaches and/or more marine sediment may enter on a high tide than leave the system on the low tide.
	Episodic floods play a key role in the long-term erosion – deposition equilibrium of estuaries, with large events (>1:20 year return period) scouring significant volumes of both catchment and marine-derived sediments during such events. Large floods also replenish floodplain sediments and can result in the scouring and formation of structures such as islands, shoals, and backwater areas. Floods also play a critical role in the removal of accumulated organic matter from estuaries.
	Sand is carried both in suspension and bed load. The load will determine the potential for sand deposition in an estuary or floodplain. Sand is likely to be deposited at the end of a high-flow event. Sand is episodically supplied to the channel from the catchment but is also transported down the channel in a "jerky conveyor belt" as sand deposits on the bed are remobilized. This driver is normally incorporated from the river assessment as an input into the estuary
	Silt is largely transported as suspended load. Normally the main source of silt during flood events is catchment erosion processes. This can be enhanced through local bed and bank disturbance through land-use change in the catchment and surrounding environs. As a general principle, there is a positive but variable relationship between suspended sediment concentration and flow discharge. Although most sediment is transported during higher flows. Once in suspension, most silt will be transported through the channel as a load; significant deposition only occurs in low-velocity areas. This driver is normally incorporated from the river assessment as an input into the estuary.

4.4 Microalgae

Microalgae, as primary producers, form the base of food chains in estuaries. Three key indicators were considered relevant:

- Phytoplankton

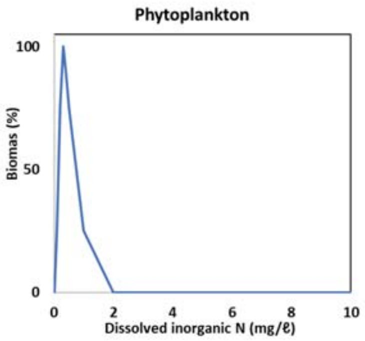
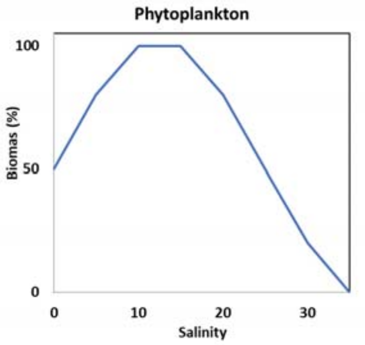
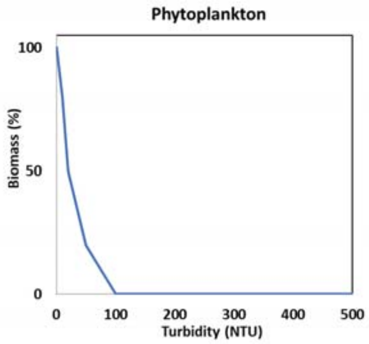
- Benthic microalgae
- Harmful algae.

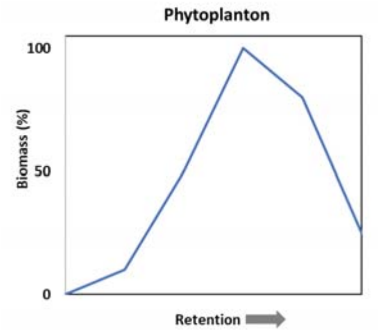
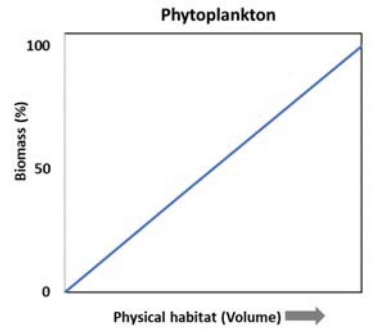
Microalgae are primarily included as a food source for higher trophic levels in EFlows assessments (Van Niekerk *et al.* 2014). The key drivers included here, therefore primarily related to those affecting biomass, and do not focus on what drives the species distribution of microalgae (e.g. salinity and marine connectivity).

4.4.1 Phytoplankton

Phytoplankton, a flora of freely floating, often minute organisms that occupies in the water column (Table 4.21). Dinoflagellates, diatoms, and cyanobacteria constitute the three main types of phytoplankton found in the photic zones of aquatic environments.

Table 4.21 Phytoplankton links and explanations

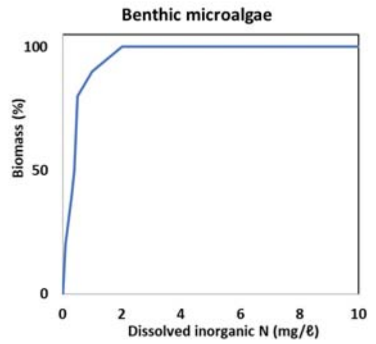
PHYTOPLANKTON	
Link and response curve	**Explanation**
	Inorganic nutrients: High nutrient loads in estuaries support high microalgal biomass (median phytoplankton chlorophyll *a* >8 µg/ℓ). Strong stratification in a nutrient-rich estuary is likely to support a dinoflagellate dominated phytoplankton community. Extended periods of low river flow and tidal exchange in a nutrient-rich estuary will accelerate the process of eutrophication in estuaries, resulting in an organic-rich and oxygen-poor environment that supports a cyanobacteria dominated microalgal community.
	Salinity: Distinct phytoplankton communities are present in marine and freshwater environments. The presence of either of these two communities in an estuary is dependent on the hydrodynamics (e.g. tidal intrusion and freshwater flow) within an estuary.
	Turbidity: Microalgal primary production is light dependent and an increase in turbidity is likely to inhibit this, resulting in a decrease in the biomass of microalgae.

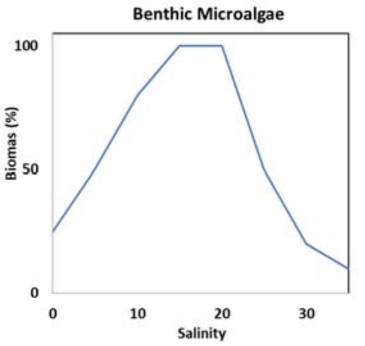
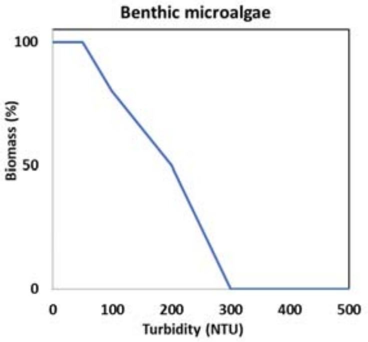
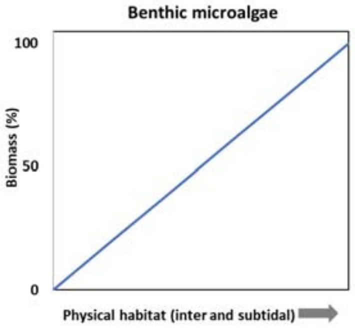
PHYTOPLANKTON	
Link and response curve	**Explanation**
	Water retention: Short water retention times favour the dominance of chlorophyte taxa in the upper and middle reaches of estuaries. Efficient intrusion of marine water in open estuaries replenishes oxygen-rich water in the lower reaches of estuaries, preventing cyanobacteria from becoming dominant.
	Physical habitat (subtidal volume/extent): When a closed estuary is breached, the reduction in water level causes a decrease in the volume of water occupied by phytoplankton, limiting the potential area for colonisation of microalgae as well as overall primary production throughout the estuary.

4.4.2 Benthic microalgae

Benthic microalgae are photosynthetic microorganisms growing in the sediment, contrarily to phytoplankton that develop in the water column. They live on or in exposed intertidal or submerged surfaces (Table 4.22).

Table 4.22 Benthic microalgae links and explanations

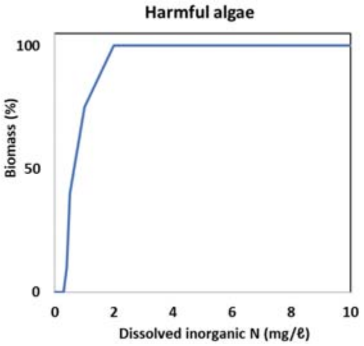
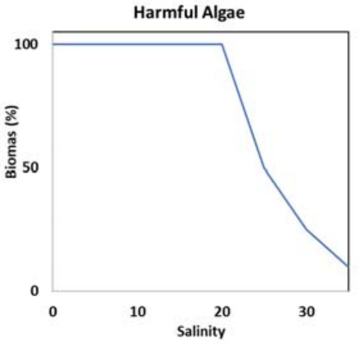
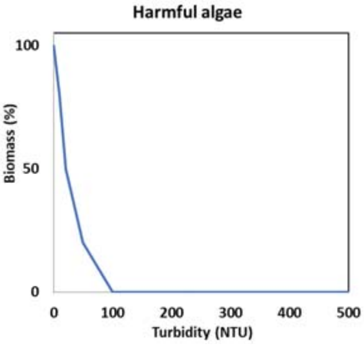
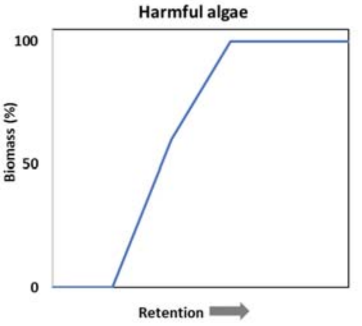
BENTHIC MICROALGAE	
Link and response curve	**Explanation**
	Inorganic nutrients: High nutrient loads in estuaries support high microalgal biomass (median intertidal benthic microalgal chlorophyll *a* >23 mg/m^2).

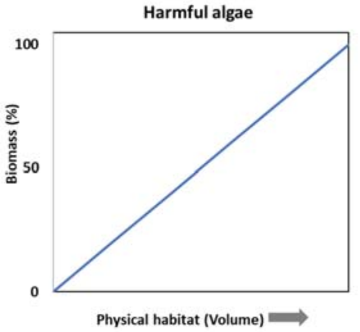
BENTHIC MICROALGAE	
Link and response curve	**Explanation**
	Salinity: Distinct microphytobenthos communities are present in marine and freshwater environments. The presence of either of these two communities in an estuary is dependent on the hydrodynamics (e.g. tidal intrusion and freshwater flow) within an estuary.
	Turbidity: Microalgal primary production is light dependent and an increase in turbidity is likely to inhibit this, resulting in a decrease in the biomass of microalgae.
	Physical habitat (intertidal extent and subtidal volume/extent): When an estuary mouth closes, or becomes constricted, it can limit the potential intertidal area and increase the amount of subtidal area for colonisation as well as impact overall primary production throughout the estuary.
Water retention: same response curve and explanation as Phytoplankton (Section 4.4.1)	

4.4.3 Harmful algae

Harmful algal blooms in estuaries, usually a result of eutrophication, have a number of direct (toxicity) and indirect (e.g. hypoxia) impacts on estuarine fauna. Blue-green Microcystis blooms, common in many estuaries, can cause skin and/or organ lesions in fish resulting in poor health, reduced reproductive success and mortalities (Table 4.23).

Table 4.23 Harmful algae links and explanations

HARMFUL ALGAE	
Link and response curve	**Explanation**
	Inorganic nutrients: Extended periods of low river flow and tidal exchange in a nutrient-rich estuary will accelerate the process of eutrophication in estuaries, resulting in an organic-rich and oxygen-poor environment that supports a cyanobacteria dominated microalgal community.
	Salinity: Distinct communities are present in marine and freshwater environments. The presence of either of these two communities in an estuary is dependent on the hydrodynamics (e.g. tidal intrusion and freshwater flow) within an estuary.
	Turbidity: Microalgal primary production is light dependent and an increase in turbidity is likely to inhibit this, resulting in a decrease in the biomass of microalgae.
	Water retention: Long water retention times favour the dominance of cyanobacteria. The intrusion of oxygen-poor ground water typically supports cyanobacteria in the microphytobenthos

HARMFUL ALGAE	
Link and response curve	**Explanation**
	Physical habitat (Subtidal volume/extent): When a closed estuary is breached, the reduction in water level causes a decrease in the volume of water occupied by phytoplankton, limiting the potential area for colonisation of microalgae as well as overall primary production throughout the estuary.

4.5 Macrophytes

Macrophyte habitats provide important ecosystem services such as filtering and detoxification. They cycle nutrients by taking them up and releasing them again through decomposition processes. They provide a nursery for fish and protected habitats for a variety of other organisms. For EFlows assessments, the following key indicators were considered most relevant:

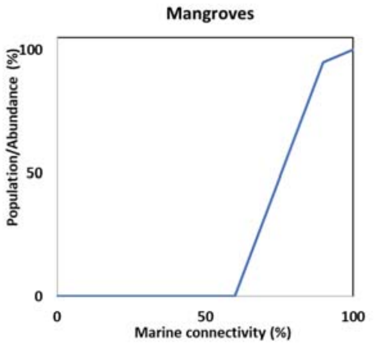
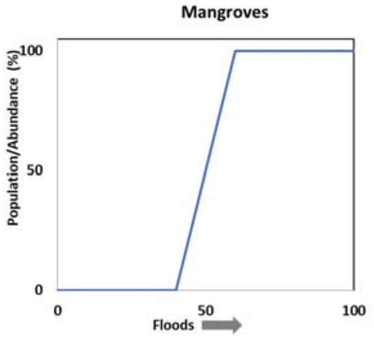
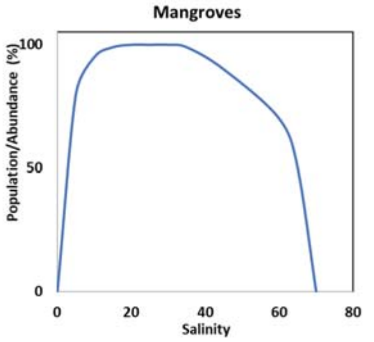
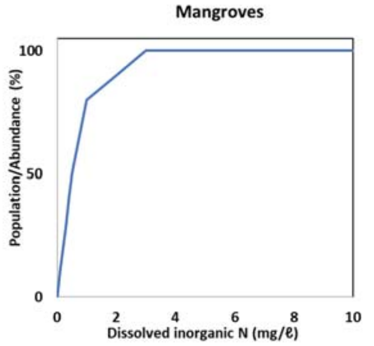
- Mangroves
- Salt marsh
- Submerged macrophytes
- Reeds and sedges
- Macroalgae
- Swamp forests.

Salt marsh, mangrove and reed and sedge wetlands protect the land from floods and sea storms and sequester carbon and serve as a source of raw materials for humans (van Niekerk *et al.* 2014).

4.5.1 Mangroves

Mangroves are trees that are established in the intertidal zone in permanently open estuaries along the west and east coast of Africa (Table 4.24). Mangrove forests protect the coastline acting as buffers against severe weather. They are extremely productive habitats that are home to a diversity of fish and invertebrate species. Mangroves are also important for filtering and improving water quality. They also have a high recreational, cultural and tourism value. More recently the value of mangrove forests as a carbon sink has been recognized. Mangroves are threatened by over-abstraction of freshwater, change in sediment inputs, overutilization such as the harvesting of mangrove wood for building material, and for removal for aquaculture and slash and burn cultivation. Climate change-driven sea level rise and temperature changes have the potential to change the distribution range of mangrove species.

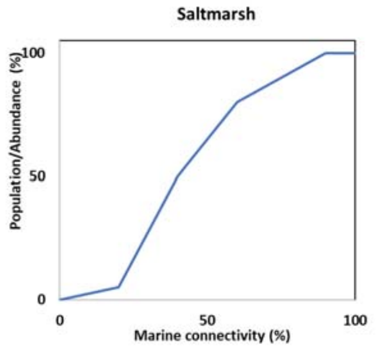
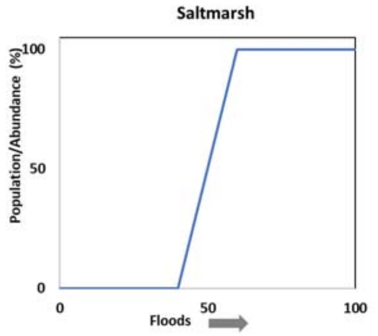
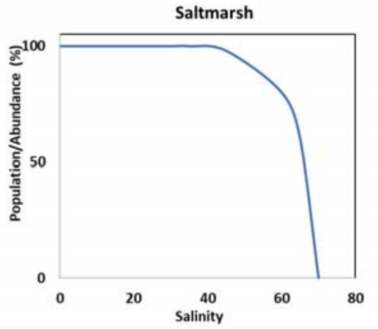
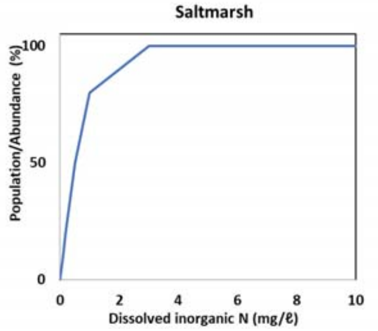
Table 4.24 Mangroves links and explanations

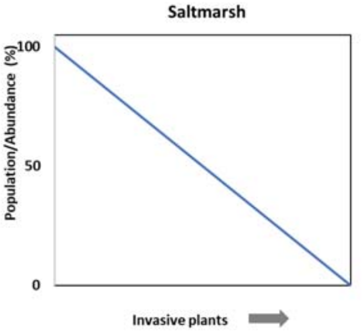
MANGROVES	
Link and response curve	**Explanation**
	Marine connectivity: Open mouth conditions create intertidal habitat. Prolonged mouth closure could result in the die-back of mangroves
	Floods: Large floods are important in flushing out salts from the mangrove area. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth. Floods would also deposit rich organic mud in estuaries and thus floods have an important nitrifying effect.
	Salinity: The longitudinal salinity gradient promotes species richness, and different macrophyte habitats are distributed along the length of the estuary.
	Inorganic nutrients: Increased nutrient inputs would increase mangrove growth. Eutrophication responses can result in epiphytic growth on pneumatophores resulting in slow growth or die-back.

4.5.2 Salt marsh

Saltmarshes are a suite of herbaceous vascular plants that are adapted to endure the extremes of salinity, desiccation and tidal flooding characterizes salt marshes (Table 4.25). Salt marsh plants show distinct zonation patterns along tidal inundation and salinity gradients. Zonation is well developed in estuaries with a large tidal range. Intertidal salt marsh occurs below mean high water spring and supratidal salt marsh above this. Salt marsh vegetation stabilizes the sediment protecting the banks of an estuary from eroding away. They are important filters of sediment and pollutants as well as zones of nutrient production and retention. Intertidal salt marsh occurs below mean high water spring and supratidal salt marsh above this.

Table 4.25 Salt marsh links and explanations

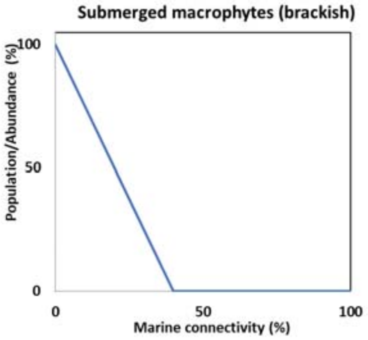
SALT MARSH	
Link and response curve	**Explanation**
	Marine connectivity: Open mouth conditions create intertidal habitat. Salt marsh species occur along a tidal inundation gradient. Prolonged mouth closure could result in the die-back of intertidal salt marsh species.
	Floods: Large floods are important in flushing out salts from the salt marsh area. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. High groundwater level and freshwater flooding maintains suitable moisture conditions for plant growth in salt marshes. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth. Floods would also deposit rich organic mud in estuaries and thus floods have an important nitrifying effect.
	Salinity: A change in salinity will influence the macrophyte habitats, e.g. salt marsh and sea grass grow better in salinity close to water. Freshwater inflow dilutes salts, preventing hypersaline conditions in salt marshes. Rainfall and evaporation on the marsh, groundwater seepage from adjacent land and the salinity of the tidal water that inundates the marsh control the sediment salinity. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas.
	Inorganic nutrients: Increased nutrient inputs would increase macrophyte growth.

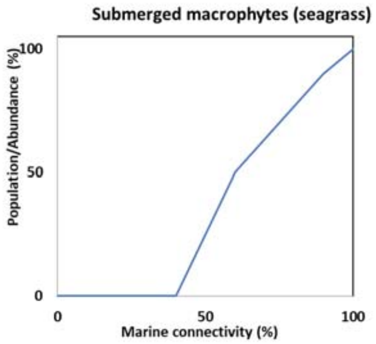
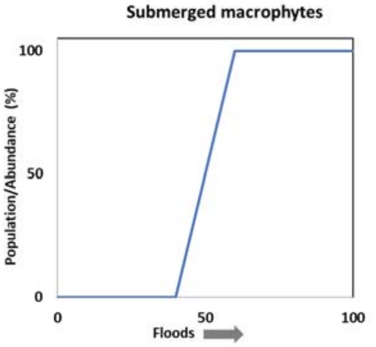
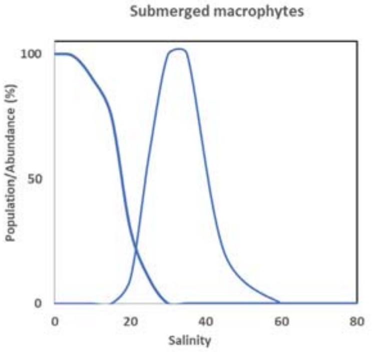
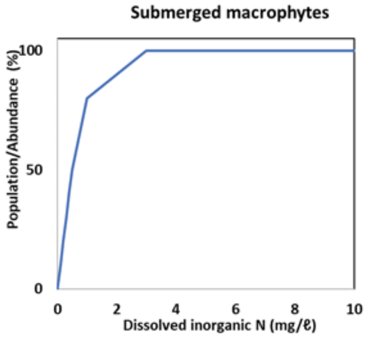
<table>
<tr><th colspan="2">SALT MARSH</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td> </td><td>Invasive plants: Loss of macrophyte habitat due to invasion by exotic species. Colonisation of disturbed floodplains or estuary margins by invasive plants.</td></tr>
</table>

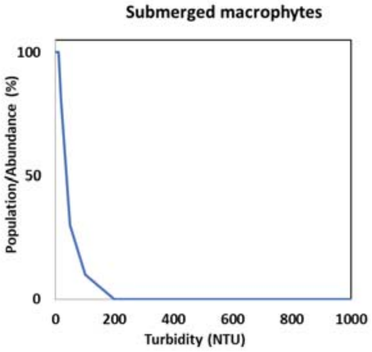
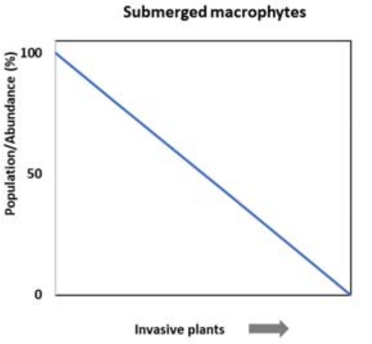
4.5.3 *Submerged macrophytes*

Plants that are rooted in both soft subtidal and low intertidal substrate and whose leaves and stems are completely submerged for most states of the tide (Table 4.26). Submerged macrophytes tend to occur in permanently open estuaries, particularly eelgrass (*Zostera capensis*) whereas *Ruppia cirrhosa* prefers the less saline and sheltered conditions of estuaries that close to the sea. *Potamogeton pectinatas* (ribbon weed, fennel pondweed) prefers fresher conditions (salinities below 10) and therefore occurs in closed systems or in the upper reaches of estuaries. Several estuarine resident faunal species have a critical dependence on vegetated habitats. Seagrass is especially important, although other vegetation can be used. In clear water systems especially, fishes have a high dependency on vegetation as a predation refuge, especially during daylight hours. However, in turbid system, habitat associations with structured habitats are generally weaker or habitat may even not be present.

Table 4.26 Submerged macrophytes links and explanations

<table>
<tr><th colspan="2">SUBMERGED MACROPHYTES</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td> </td><td>Marine connectivity: Open mouth conditions cause die-back of brackish species.</td></tr>
</table>

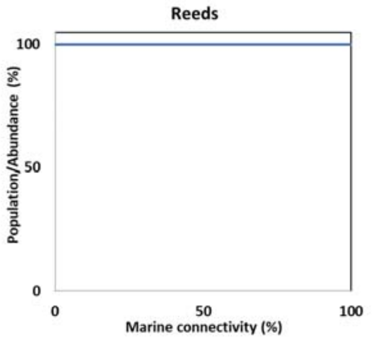
SUBMERGED MACROPHYTES	
Link and response curve	**Explanation**
	Marine connectivity: Open mouth conditions cause an increase in seagrass.
	Floods: Large floods are important in flushing out salts from the salt marsh area and preventing the encroachment of reeds and sedges into the main river channel. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. High groundwater level and freshwater flooding maintains suitable moisture conditions for plant growth in salt marshes. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth. Floods would also deposit rich organic mud in estuaries and thus floods have an important nitrifying effect.
	Salinity: A change in salinity will influence the macrophyte habitats. Many submerged macrophytes prefer fresh to brackish conditions below 15. Seagrass prefers a more saline environment.
	Inorganic nutrients: Increased nutrient inputs would increase submerge macrophyte growth. Eutrophication responses are an increase in plant growth.

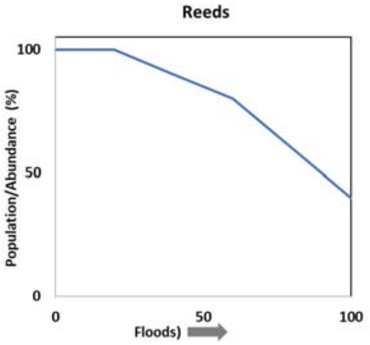
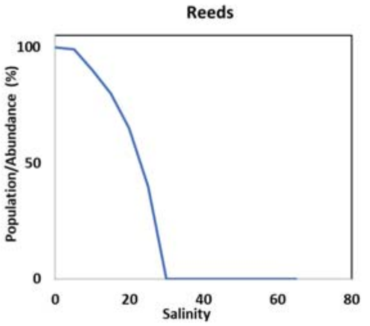
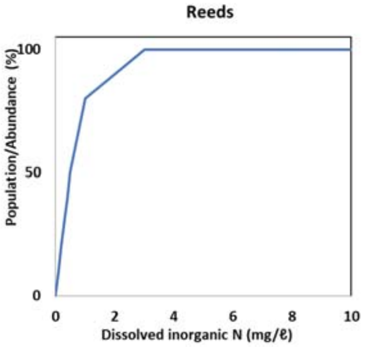
<table>
<tr><th colspan="2">SUBMERGED MACROPHYTES</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td> </td><td>Turbidity: Increase sediment load within the water column results in a reduction in the photic zone and will limit submerged macrophyte establishment and distribution. Submerged macrophyte distribution is naturally limited in turbid estuaries, however, catchment degradation can increase silt load.</td></tr>
<tr><td> </td><td>Invasive plants: Loss of macrophyte habitat due to invasion by exotic species. Colonisation of disturbed floodplains or estuary margins by invasive plants.</td></tr>
</table>

4.5.4 *Reeds and sedges*

Reeds, sedges and rushes are important in the freshwater and brackish zones of estuaries, providing structure and shelter while protecting banks from erosion (Table 4.27). Because they are often associated with freshwater input, they can be used to identify freshwater seepage sites along estuaries and an indicator of salinity creep. The dominant species are the common reed *Phragmites australis*, *Schoenoplectus scirpoides* and *Bolboschoenus maritimus.*

Table 4.27 Reeds and sedges links and explanations

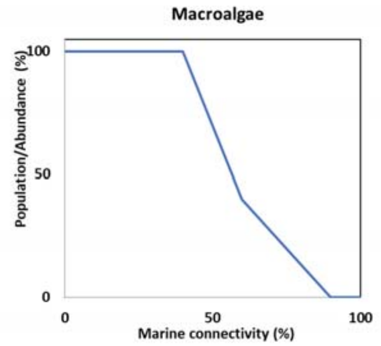
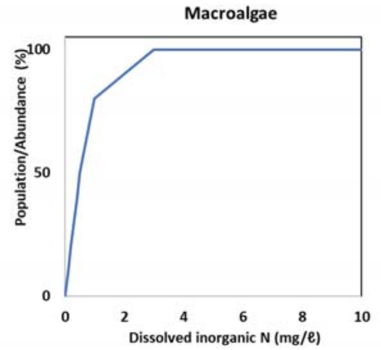
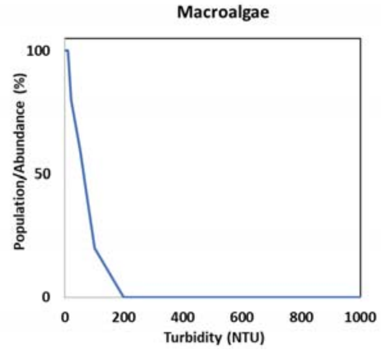
<table>
<tr><th colspan="2">REEDS AND SEDGES</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td> </td><td>Marine connectivity: Largely unresponsive to mouth state. Prolonged mouth closure in some systems coupled with elevated water levels can cause die-back.</td></tr>
</table>

REEDS AND SEDGES	
Link and response curve	**Explanation**
	Floods: Large floods are important for preventing the encroachment of reeds and sedges into the main river channel. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth.
	Salinity: A change in salinity will influence the macrophyte habitats, e.g. reeds and sedges grow better in brackish water whereas salt marsh and sea grass grow better in salinity close to water. Development and runoff can often decrease salinity leading to reed expansion. Reeds and sedges are sensitive to increases in salinity but can survive if their roots and rhizomes are located in salinity less than 20. However, if freshwater seepage is reduced then it may lead to dieback.
	Inorganic nutrients: Increased nutrient inputs would increase growth particularly in areas of freshwater seepage (i.e. reeds and sedges). Eutrophication responses are an increase in plant growth, e.g. expansion of reeds.

4.5.5 Macroalgae

These can be free floating or attached to rocks and other substrates (Table 4.28). Filamentous macroalgae often form algal mats and increase in response to nutrient enrichment or calm sheltered conditions when the mouth of an estuary is closed. Typical genera include *Enteromorpha* and *Cladophora*. Many marine species can get washed into an estuary and providing the salinity is high enough, can proliferate. These include *Codium*, *Caulerpa*, *Gracilaria* and *Polysiphonia.*

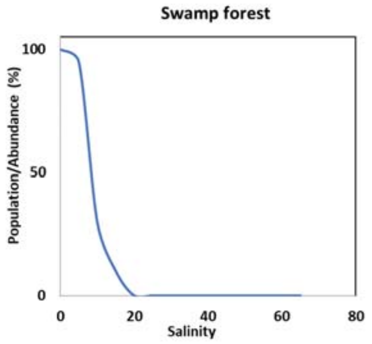
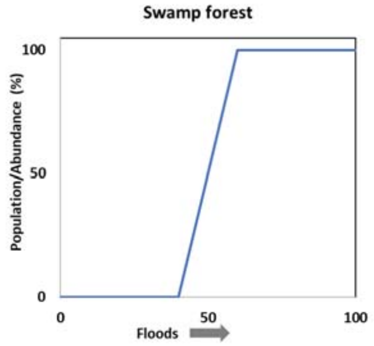
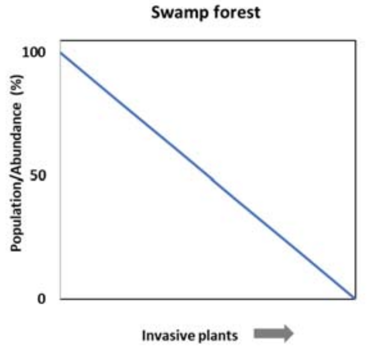
Table 4.28 Macroalgae links and explanations

MACROALGAE	
Link and response curve	**Explanation**
	Marine connectivity: Closed mouth conditions would promote the growth and proliferation of macroalgae.
	Inorganic nutrients: Inorganic nutrients (especially N and P) are known to stimulate the abundance of ephemeral and epiphytic macroalgae. *Ulva* and *Cladophora* often form accumulations due to their filamentous nature and higher nutrient uptake rates than algae with thicker thalli. These accumulations can reduce the water quality of estuaries, by depleting the oxygen in the water column upon decomposition.
	Turbidity: Increase sediment load within the water column results in a reduction in the photic zone and will limit macroalgae establishment and distribution. Distribution is naturally limited in turbid estuaries, however, catchment degradation can increase silt load.
Floods: same response curve and explanation as Submerged macrophytes (Section 4.5.3)	

4.5.6 Swamp forests

Swamp forests are freshwater ecosystems associated with estuaries in the subtropical and tropical regions, including species such as *Barringtonia racemosa*, *Hibiscus tiliaceous, Ficus trichopoda* and *Syzigium cordatum*. In systems with little submerged macrophytes they play an important role in detritus input in the form of leaf litter (Table 4.29). This habitat plays an important role in riparian erosion control and flood attenuation.

Table 4.29 Swamp forests links and explanations

SWAMP FORESTS	
Link and response curve	**Explanation**
	Salinity: Increased salinity will cause dieback in swamp forest
	Floods: Large floods are important in flushing out salts from swamp forests. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth. Floods would also deposit rich organic mud in estuaries and thus floods have an important nitrifying effect.
	Invasive plants: Loss of macrophyte habitat due to invasion by exotic species. Colonisation of disturbed floodplains or estuary margins by invasive plants.

4.6 Fish

Approximately 50 of the 150 estuarine-associated fish species that regularly occur in estuaries in the region are endemic to Southern Africa. In fact, some species are confined to only a few systems. Estuarine fish diversity in Southern Africa declines south and westwards with few species typical of the tropical and subtropical east coast bioregions occurring on South Africa's Warm-Temperate south-east coast or Cool-temperate west coast (Day 1981, Whitfield 1994). Conversely, biological and fisheries productivity are highest in the Cool-temperate bioregion and decline eastward in the warm and subtropical bioregions (Lamberth and Turpie 2003). Within each region, fish productivity is higher in permanently open versus temporarily open-closed systems (Harrison and Whitfield 2006). Key response indicators most relevant to fish, organised as per key groupings below (Table 4.30):

- IA. Estuarine residents (breeding only in estuaries)

- IB. Estuarine residents (breeding in estuaries and the sea)
- IIA. Estuary dependent marine species
- IIB & C. Estuarine associated species
- III. Marine migrants
- IV. Freshwater species
- V. Catadromous species.

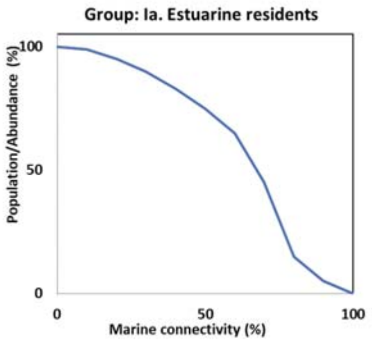
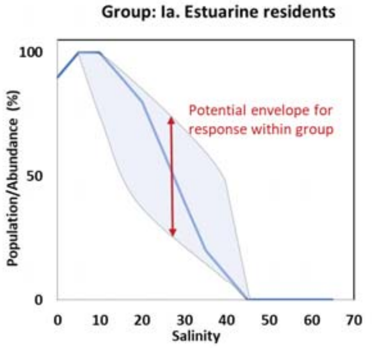
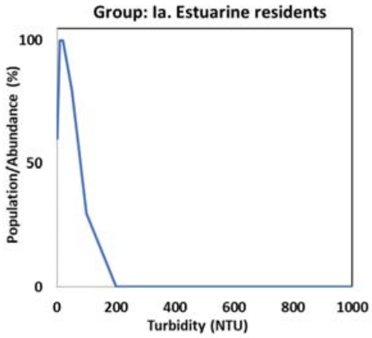
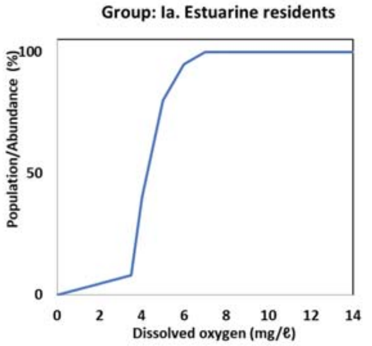
Table 4.30 Fish indicators for EFlows assessments in Southern Africa (adapted from Whitfield 1994)

INDICATOR	DESCRIPTION
I IA IB	Truly estuarine species, which breed in Southern African estuaries; subdivided as follows: a. Resident species which have not been recorded breeding in the freshwater or marine environment b. Resident species which have marine or freshwater breeding populations
II IIA IIB IIC	Euryhaline marine species which usually breed at sea with the juveniles showing varying degrees of dependence on Southern African estuaries; subdivided as follows: a. Juveniles dependant on estuaries as nursery areas b. Juveniles occur mainly in estuaries, but are also found at sea c. Juveniles occur in estuaries but are more abundant at sea
III	Marine species which occur in estuaries in small numbers but are not dependent on these systems
IV	Euryhaline freshwater species that can penetrate estuaries depending on salinity tolerance. Includes some species which may breed in both freshwater and estuarine systems. Includes the following subcategories: • Indigenous • Translocated from within Southern Africa • Alien
V	Obligate catadromous species (eels) which use estuaries as transit routes between the marine and freshwater environments

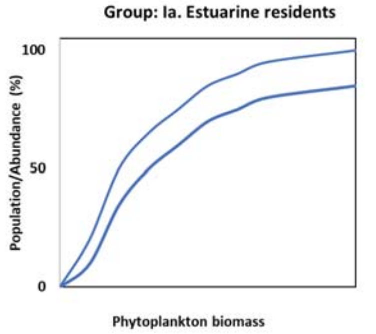
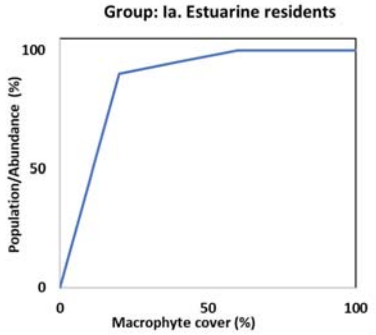
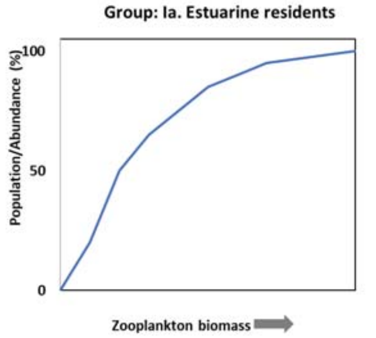
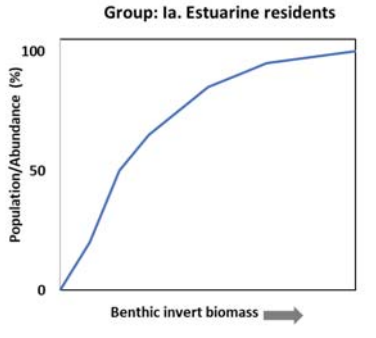
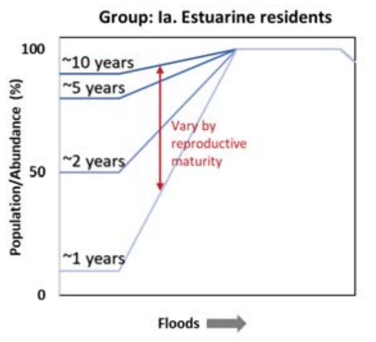
4.6.1 IA. Estuarine residents (breed only in estuaries)

These are truly estuarine species that reside in the Southern African estuaries. This indicator represents species that breed in the estuary species and have not been recorded to breed in freshwater or marine environments (Table 4.31).

Table 4.31 IA. Estuarine residents (breed only in estuaries) links and explanations

IA. ESTUARINE RESIDENTS (BREED ONLY IN ESTUARIES)	
Link and response curve	**Explanation**
 Group: Ia. Estuarine residents 	Marine connectivity: Species proliferate under closed mouth conditions
 Group: Ia. Estuarine residents 	Salinity: Resident and estuary associated marine species are very tolerant of salinities in the range 1-35.
 Group: Ia. Estuarine residents 	Turbidity: Turbidity plays a strong role in influencing estuarine fish assemblages. Most estuarine species are tolerant of a wide range of turbidity.
 Group: Ia. Estuarine residents 	Dissolved oxygen: Most resident species become stressed when oxygen drops below 4 mg/ℓ. However, surface respiration is an adaptation by most estuarine and freshwater species to overcome hypoxia. Skin respiration is also an adaptation in some species, e.g. Gobiiformes. Mudskippers & gobies whereas sole gill-morphology allows survival in hypoxic conditions. The suite of behavioural & physiological adaptations in fish includes tachycardia (fast heartbeat) & bradycardia (slow heart beat), angiogenesis (growth of new blood vessels: buccal, pharyngeal, opercular, gut and/or skin), gill remodelling (respiratory surface area) and changes in metabolic rate.

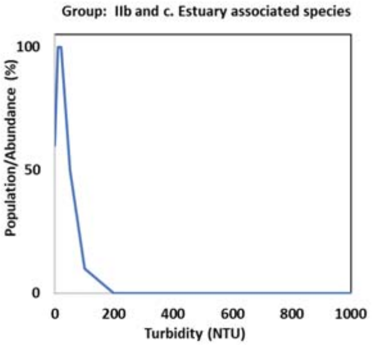
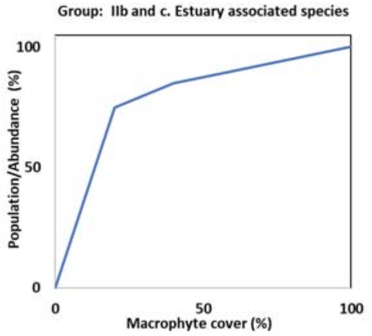
IA. ESTUARINE RESIDENTS (BREED ONLY IN ESTUARIES)

Link and response curve	Explanation
	Phytoplankton: Phytoplankton is also a food source for filter-feeding fish and invertebrates. Fish also benefit indirectly from proliferation of invertebrates that feed on phytoplankton. Omnivorous filter-feeding fish will out-compete selective feeders during periods of high phytoplankton biomass.
	Macrophyte cover: Juveniles of most fish species find refuge in littoral macrophyte beds during the daytime but move into open water or to the surface during the night as oxygen levels drop in the littoral zone.
	Zooplankton biomass: Most juvenile fish in estuaries feed on zooplankton. Filter and particulate feeders benefit from increased zooplankton biomass. Many fish species can switch between filter and targeted, selective feeding modes to take advantage of dominant zooplanktonic food sources. One caveat is that predatory marine zooplankters (e.g. chaetognaths) may have a devastating impact on recruiting fish larvae. Jellyfish may do the same.
	Benthic invertebrate biomass: Many estuary-associated fish species feed on benthic invertebrates and will thus benefit from increases in benthic invertebrate biomass. Burrow associated fish (symbiotic relationships, e.g. gobies) diversity and numbers will vary according to that of benthic invertebrates (e.g. sand prawn).
	Floods: The larvae of resident species are washed into the sea at the onset of floods, but the size of floods determines the size of the recruitment signal post-flood.

4.6.2 *IB. Estuarine residents (breed in estuaries and sea)*

Indicator represents truly estuarine species, which breed in Southern African estuaries (Table 4.32). However, these estuarine resident species also have marine or freshwater breeding populations.

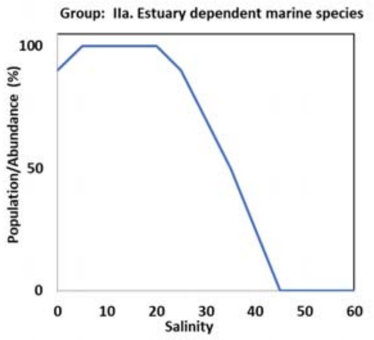
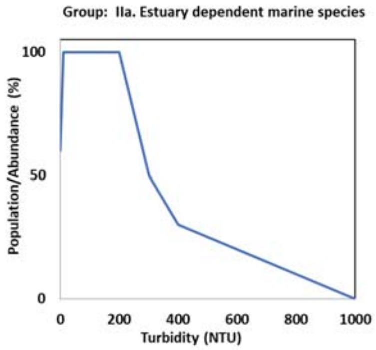
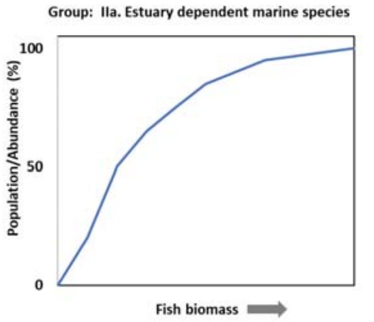
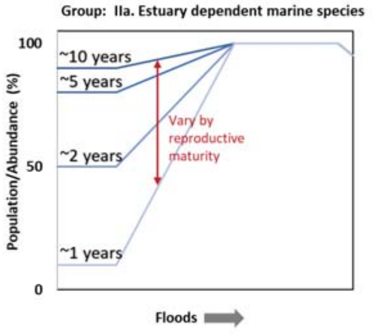
Table 4.32 IB. Estuarine residents (breed in estuaries and sea) links and explanations

IB. ESTUARINE RESIDENTS (BREED IN ESTUARIES AND SEAS)	
Link and response curve	**Explanation**
	Turbidity: Turbidity preferences and tolerances vary among species. High turbidity tolerance (physiological adaptation) among some species affords them refuge and access to a specialist ecological niche.
	Macrophyte cover: Juveniles of most fish species find refuge in littoral macrophyte beds during the daytime but move into open water or to the surface during the night as oxygen levels drop in the littoral zone.
Marine connectivity: Salinity: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Salinity: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Dissolved oxygen: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Phytoplankton: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Benthic invertebrate biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Floods: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	

4.6.3 *IIA. Estuary dependent marine species*

These are euryhaline marine species that breed at sea, but with juveniles that have varying degrees of dependence on Southern African estuaries (Table 4.33). For this indicator juveniles are dependent on estuaries as nursery areas.

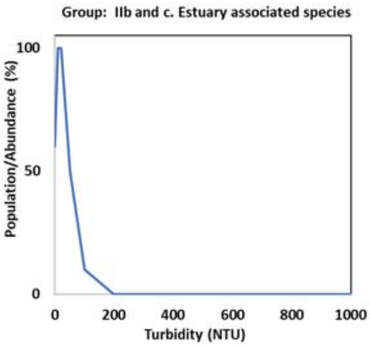
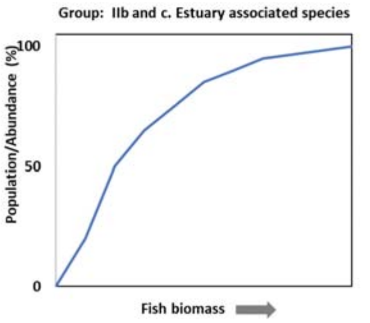
Table 4.33 IIA. Estuary dependent marine species links and explanations

IIA. ESTUARY DEPENDENT MARINE SPECIES	
Link and response curve	**Explanation**
	Salinity: Estuary associated marine species very tolerant of salinities in the range 1-35.
	Turbidity: Turbidity preferences and tolerances vary among species. High turbidity tolerance (physiological adaptation) among some species affords them refuge and access to a specialist ecological niche at the highly turbid range of some estuaries.
	Fish biomass: Fish biomass dominated by estuary associated marine species that utilise different food chains, e.g. groovy mullet *Chelon dumerili* is a detritivore, spotted grunter *Pomadasys commersonnii* a zoobenthivore and dusky kob *Argyrosomus japonicas* a piscivore. The piscivores benefit from the high biomass of estuarine resident and small marine migrants in the estuary.
	Floods: Juvenile marine species use floodwaters entering the sea as a cue for locating and migrating into estuaries, whereas adults and sub-adults exit during floods or use them to overcome obstacles to move upstream. Major river flooding associated with high sediment loads can cause gill clogging and hypoxia for fish in the estuary. Large aggregations of kob and other fish with preferences occur immediately adjacent to estuary mouths during floods.
Marine connectivity: same response curve and explanation as IA. Estuarine residents (Section 7.6.1).	
Dissolved oxygen: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Macrophyte cover: same response curve and explanation as IB. Estuarine residents (Section 4.6.2)	
Phytoplankton: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Benthic invertebrate biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	

4.6.4 IIB & C. Estuarine associated species

This indicator represents species where juveniles occur mainly in estuaries, but are also found at sea (IIB) and also those species where juveniles occur in estuaries but are more abundant at sea (IIC).

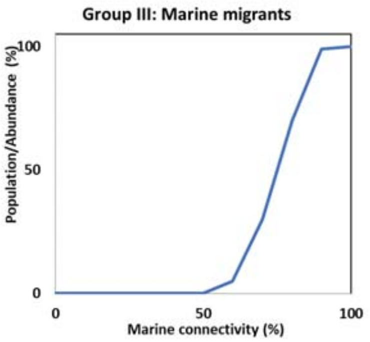
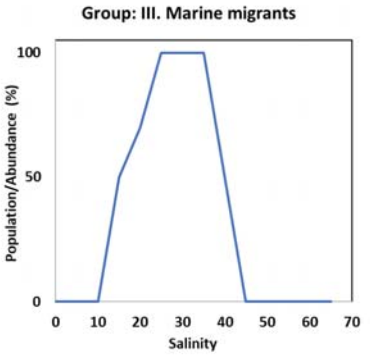
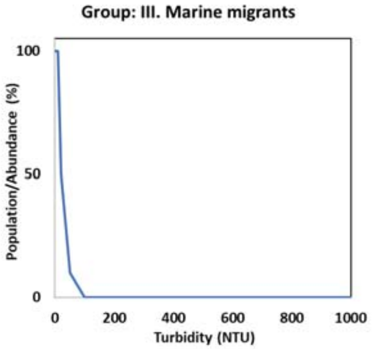
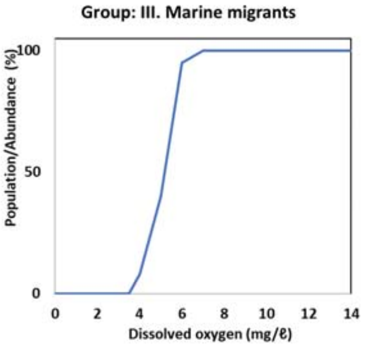
Table 4.34 IIB & C. Estuarine associated species links and explanations

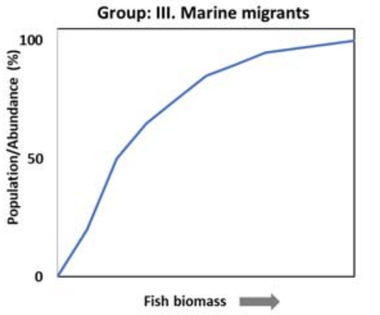
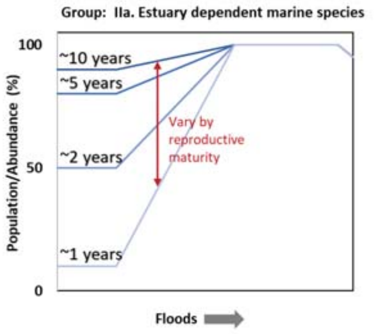
<table>
<tr><th colspan="2">IIB AND C. ESTUARINE ASSOCIATED SPECIES</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td>
</td><td>Turbidity: Turbidity preferences and tolerances vary among species. High turbidity tolerance (physiological adaptation) among some species affords them refuge and access to a specialist ecological niche.</td></tr>
<tr><td>
</td><td>Fish biomass: Fish biomass dominated by estuary associated marine species that utilise different food chains, e.g. groovy mullet <i>Chelon dumerili</i> is a detritivore, spotted grunter <i>Pomadasys commersonnii</i> a zoobenthivore and dusky kob <i>Argyrosomus japonicas</i> a piscivore. The piscivores benefit from the high biomass of estuarine resident and small marine migrants in the estuary.</td></tr>
<tr><td colspan="2">Marine connectivity: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Salinity: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Dissolved oxygen: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Macrophyte cover: same response curve and explanation as IB. Estuarine residents (Section 4.6.2)</td></tr>
<tr><td colspan="2">Phytoplankton: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Benthic invertebrate biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Floods: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
</table>

4.6.5 III. Marine migrants

These are marine species that occur in estuaries in small numbers but are not dependent on these systems (Table 4.35).

Table 4.35 III. Marine migrants species links and explanations

III. MARINE MIGRANTS	
Link and response curve	**Explanation**
	Marine connectivity: Abundance and richness of marine migrant communities increase with marine connectivity and decline with frequent, aseasonal and prolonged mouth closure.
	Salinity: Tend to stay as close to 35 as possible. Stressed at less than 20.
	Turbidity: Generally prefer low turbidity
	Dissolved oxygen: Little tolerance to low oxygen levels/hypoxia

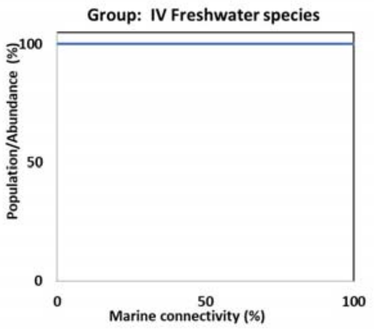
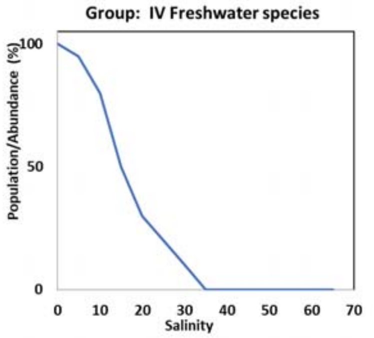
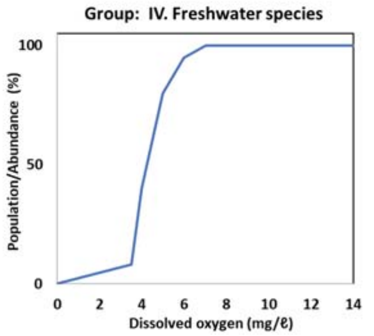
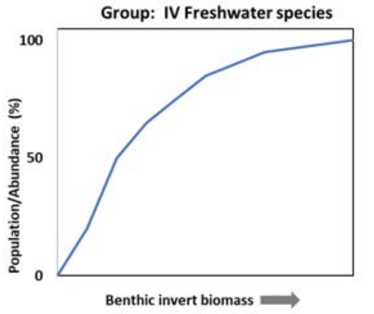
<table>
<tr><th colspan="2">III. MARINE MIGRANTS</th></tr>
<tr><th>Link and response curve</th><th>Explanation</th></tr>
<tr><td>
</td><td>Fish biomass: Fish biomass dominated by estuary associated marine species that utilise different food chains, e.g. groovy mullet <i>Chelon dumerili</i> is a detritivore, spotted grunter <i>Pomadasys commersonnii</i> a zoobenthivore and dusky kob <i>Argyrosomus japonicas</i> a piscivore. The piscivores benefit from the high biomass of estuarine resident and small marine migrants in the estuary.</td></tr>
<tr><td>
</td><td>Floods: Juvenile marine use floodwaters entering the sea as a cue for locating and migrating into estuaries, whereas adults and sub-adults exit during floods.</td></tr>
<tr><td colspan="2">Macrophyte cover: same response curve and explanation as IB. Estuarine residents (Section 4.6.2)</td></tr>
<tr><td colspan="2">Phytoplankton: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Benthic invertebrate biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
</table>

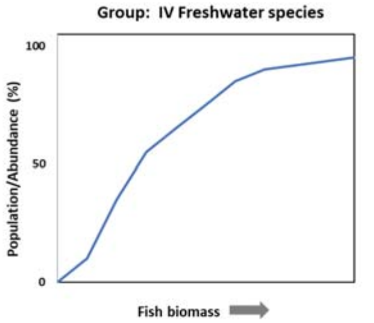
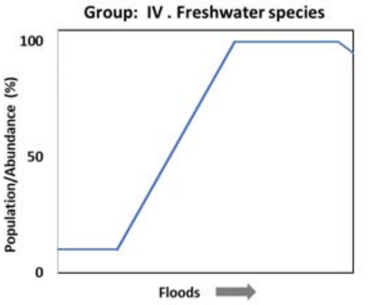
4.6.6 IV. Freshwater species

Euryhaline freshwater species can penetrate estuaries depending on salinity tolerance (Table 4.36). Includes some species which may breed in both freshwater and estuarine systems. Includes the following subcategories:

- Indigenous
- Translocated from within Southern Africa
- Alien.

Table 4.36 IV. Freshwater species links and explanations

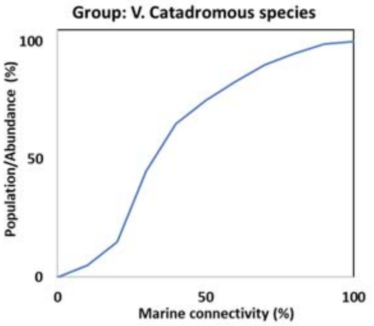
IV. FRESHWATER SPECIES	
Link and response curve	**Explanation**
	Marine connectivity: Freshwater species insensitive to mouth state
	Salinity: Highly variable. Most prefer a salinity < 10. Increase in abundance at low salinity levels and decline at higher salinity. However, some species like Cichlidae, e.g. Mozambique & redbreast tilapia, are tolerant of, and may thrive in hypersalinity.
	Dissolved oxygen: Surface respiration is an adaptation by some estuarine and freshwater species to overcome hypoxia. Some indigenous species adapted to low oxygen, e.g. air-breathing organs, skin respiration and aestivation, e.g. Galaxiidae, Clariidae.
	Benthic invertebrate biomass: Many freshwater fish species feed on benthic invertebrates and will thus benefit from increases in benthic invertebrate biomass.

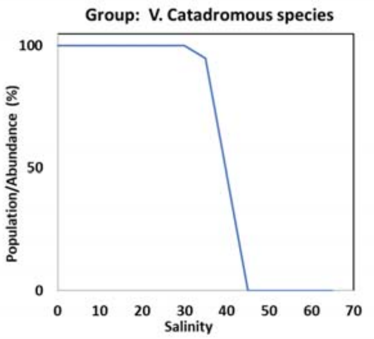
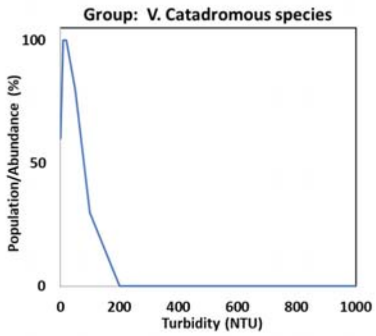
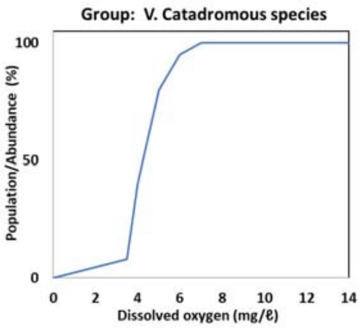
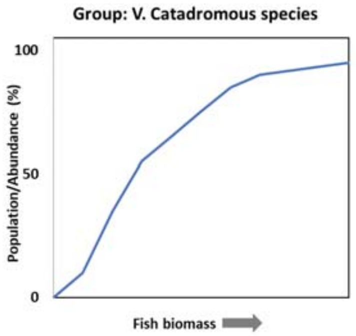
IV. FRESHWATER SPECIES	
Link and response curve	**Explanation**
	Fish biomass: Introduced freshwater fish may outcompete and eat estuary fish but also result in a substantial increase in biomass, e.g. the sharp tooth catfish *Clarias gariepinus*. Introduced species are usually more tolerant of poor water quality, thereby becoming the dominant fish in some systems.
	Floods: Floods can act as migratory cue for species that use parts of the estuary. Large floods may flush some individuals downstream into the estuary and ultimately into marine environment resulting in short term decline in abundance.
Turbidity: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Macrophyte cover: same response curve and explanation as IB. Estuarine residents (Section 4.6.2)	
Phytoplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	
Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)	

4.6.7 V. Catadromous species

Obligate catadromous species (eels) which use estuaries as transit routes between the marine and freshwater environments (Table 4.37).

Table 4.37 V. Catadromous species links and explanations

V. CATADROMOUS SPECIES	
Link and response curve	**Explanation**
	Marine connectivity: Catadromous species, i.e. Anguillidae eels require connectivity for juvenile elver recruitment and return migration of adult silver eels to spawn in the sea.

<table>
<tr><td colspan="2">V. CATADROMOUS SPECIES</td></tr>
<tr><td>Link and response curve</td><td>Explanation</td></tr>
<tr><td> </td><td>Salinity: Catadromous species move through freshwater into the estuary and then into the sea and so are tolerant of a range of salinities.</td></tr>
<tr><td> </td><td>Turbidity: Tolerant of a wide range of turbidity.</td></tr>
<tr><td> </td><td>Dissolved oxygen: Surface respiration is an adaptation by some estuarine and freshwater species to overcome hypoxia. Some indigenous species adapted to low oxygen, e.g. air-breathing organs, skin respiration and aestivation, e.g. Galaxiidae, Clariidae.</td></tr>
<tr><td> </td><td>Fish biomass: Introduced freshwater fish may outcompete and eat estuary fish but also result in a substantial increase in biomass, e.g. the sharp tooth catfish <i>Clarias gariepinus</i>. Introduced species are usually more tolerant of poor water quality, thereby becoming the dominant fish in some systems.</td></tr>
<tr><td colspan="2">Phytoplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Aquatic macrophyte cover: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Zooplankton biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Benthic invertebrate biomass: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
<tr><td colspan="2">Floods: same response curve and explanation as IA. Estuarine residents (Section 4.6.1)</td></tr>
</table>

4.7 Social

Estuaries provide a wide variety of ecosystem services that grant economic, cultural, and ecological benefits. For EFlows assessments, the following key indicators were considered most relevant:

- Fisheries value
- Plant resource value
- Carbon retention value.

4.7.1 Fisheries value

Estuaries provide nursery areas for numerous species of fishes which are exploited by recreational and commercial harvesting in the inshore marine environment. The indicators that may contribute to positively the Fisheries value include the following indicators:

- IA. Estuarine residents (breed only in estuaries)
- IB. Estuarine residents (breed in estuaries and the sea)
- IIA. Estuary dependent marine species
- IIB. and C Estuarine associated species
- III. Marine migrants
- IV. Freshwater species
- V. Catadromous species.

The indicators and the corresponding strength of the response curves should be determined based on a combination of their presence in the estuary and representation in the local fisheries. For example, certain estuaries are key fisheries for anguillid eels (i.e. V. Catadromous species), whereas they may be absent from other estuaries.

4.7.2 Plant resource value

Estuarine plants including mangrove, reeds, salt marshes provide fuelwood, timber, charcoal, building and materials. They also may provide flood control and erosion protection. The indicators that may contribute positively to the Plant resource value include the following indicators:

- Mangroves
- Reeds and sedges
- Salt marsh

The indicators and the corresponding strength of the response curves can be determined based on presence of the indicator in the estuary, access to it and use/demand by local communities. For example, certain communities may be highly dependent on reeds and sedges for housing and on mangroves for firewood, whereas others may not be due to availability of accessible alternatives.

4.7.3 Carbon resource value

Estuary sediments can store carbon more effectively than sediments in forests and, if undisturbed, they can store carbon below ground for thousands of years. Coastal habitats that capture and store this “blue carbon” in marine plants and sediments include mangroves, sea grasses and estuaries. The indicators that may contribute to the Carbon resource value include the following indicators:

- Mangroves
- Salt marsh
- Submerged macrophytes
- Reeds and sedges
- Swamp forests.

5 REVIEW AND TESTING

The indicators, links and response curves contained in this report are being reviewed and tested in two ways 1) peer review and 2) test cases. In all likelihood, the indicators, links and response curves provided in this progress report will change based on the outcome of these review processes.

5.1 Peer review – rivers

Specialist reviews are being conducted sequentially given the hierarchical nature of the disciplines:

- Geomorphology indicators, links and response curves were reviewed by Dr Lois Koehnken
- Riverine vegetation indicators, links and response curves were reviewed by Dr Karl Reinecke
- Macroinvertebrate and algal indicators, links and response curves were reviewed by Dr Justine Ewart-Smith
- Fish indicators, links and response curves were reviewed by Dr. Bruce Paxton.

5.2 Peer review – estuaries

Specialist reviews were conducted sequentially given the hierarchical nature of the disciplines:

- Physical habitat indicators, links and response curves were reviewed by Prof. Lara van Niekerk
- Water quality indicators, links and response curves were reviewed by Prof. Susan Taljaard
- Microalgal indicators, links and response curves were reviewed by Dr Daniel Lemley
- Estuarine macrophyte indicators, links and response curves were reviewed by Prof. Janine Adams
- Fish indicators, links and response curves were reviewed by Prof. Steve Lamberth and Steven Weerts.

5.3 Test cases

The generic indicators, links and response curves are being applied and tested in three EFlows assessments, *viz*.:

- Services for an integrated flows assessment to facilitate the development and agreement of “objective flows” at key sites in the Pungwe Basin, Zimbabwe and Mozambique. Client: Global Water Partnership Southern Africa.
    - Completion date: September 2023.
- Determination of Water Resource Classes, Reserve and Resource Quality Objectives Study for Secondary Catchments A5-A9 within the Limpopo Water Management Area (WMA 1) and Secondary Catchment B9 in the Olifants Water Management Area (WMA 2), South Africa. Client: South African Department of Waters and Sanitation.
    - Completion date: June 2024 (DRIFT set up completion – October 2023).
- Cumulative Impact Assessment of the Mpatamanga Hydropower Plant on the Shire River Basin, Malawi. Client: Mpatamanga Hydropower Limited, through Multiconsult.
    - Completion date: June 2024 (DRIFT set up completion – December 2023).

6 RECOMMENDATIONS

6.1 Rivers

6.1.1 Monitoring and validation

More than 50 years after the start of EFlows science, the vast majority of models and other applications used to predict changes in river and estuaries ecosystems in response to changes in the flow of their waters and sediments are still reliant on expert opinion for indicators and response curves. This despite the construction of hundreds of dams on river over that period, each one of which provided an opportunity to test these relationships and improve the predictive capacity of the models. With one or two notable exceptions, funding has not been available to monitor the changes wrought by these structures, and hence the numerous opportunities to improve the science of EFlows have largely been ignored.

Comprehensive monitoring of real-life situations is required to validate and refine the understanding of how these systems react to changes in the flow of water and sediments linked with, *inter alia*, catchment activities, water-resource development and climate change. We urge funders of all forms to recognise the value of funding, well-designed and resourced focused research and monitoring on EFlows-related relationships.

6.1.2 Promote use

The acknowledged limitations notwithstanding, the generic relationships presented on this report provide rapid access to a fairly detailed understanding of SADC rivers and estuaries developed by a community of scientists over >40 years that can greatly enhance general understanding of how these ecosystems may respond to human interventions. As such, their use should be promoted over and above “black-box” methods that provide convenient but flawed answers and do not promote understanding of how and why these ecosystems function.

6.1.3 Curation of the generic library

The library of indicators and response curves is a starting point developed from projects in the professional and academic sphere. They can be and should be improved through applications, and ideally through monitoring the response of ecosystems to changes in the flow of water and sediments. When applied, if the curves are adjusted based on data, literature or expert opinion, these changes should be documented in an ongoing process to create a centralised repository of information on how and why river and estuarine ecosystems respond the way they do to human intervention. Accordingly, it would be greatly appreciated if any such changes are communicated to the study team (admin@southernwaters.co.za) so that they may be included or added to the generic library to benefit the EFlows community and enhance understanding of river and estuarine ecosystems.

6.1.4 Hydraulics

The generic response curves for rivers presented here do not include links to hydraulic indicators as these data tend to be highly site-specific. Future direction can include generating methods for translating hydrology into ‘generic’ hydraulic indicators. This would also facilitate the expansion of the library to include wetlands and floodplains.

6.2 Estuary

6.2.1 Estuarine typology

Estuary ecosystem types serve as surrogates for ecosystem processes and the biodiversity associated with them. In turn, the understanding of estuary ecosystem type processes facilitates the broad scale assessment of estuary resilience to anthropogenic pressures. The typing of estuaries also strives to identify which systems are similar to provide a proxy for the lack of species and abundance data for some components of the ecosystem biodiversity, e.g. meiofauna. Typing or classification schemes assist with the identification of monitoring requirements for management purposes.

- Collaboration with Southern African regional estuarine specialists are needed to refine ecosystem typology including conducting a specialist’s workshop(s) to validate functional types assigned to each estuary, ideally, this should be done at the country level. This includes ongoing global collaboration with experts to refine the list of estuaries that can close along this coastline.

6.2.2 Drivers and input data

While some generic relationships can be anticipated, estuarine flow-driver relationships are site-specific and often require extensive *in situ* measurements and/or hydrodynamic modelling to establish high-confidence flow-driver relationships. Future investments in the measuring and monitoring of the physical process would assist in the refinement of regional conceptual models and calibration of numerical models needed to verify the flow driver relationships.

Research in estuarine and coastal sedimentary processes lags behind hydrodynamic and biological prediction capabilities, reflecting a need for focused research. Progress is hindered by the absence of long-term calibration data sets (i.e. estuary bathymetry, fluvial sediment loads) and a relatively young developing discipline. This provides multiple research opportunities to investigate the role of floods in the various types of estuaries, the rate of sediment accretion vs sea level rise, estimating the synergistic/ antagonistic impacts of dam development and resultant sediment trapping and flow modification in conjunction with changes in land-use, land-cover and flood regimes under a future changing climate.

6.2.3 Ecological indicators and response curves

Drawing from existing published literature and historical EFlows studies a range of ecological indicators for abiotic and biotic processes were selected and generic responses were developed. These curves will require refinement in estuary-specific applications as both abiotic and biotic responses can vary widely across the types of estuaries in the region. Regional expert workshops may assist in refining the selection of indicators and the response curves, but ideally this should be further refined by *in situ* field measurements and laboratory studies to refine the driver-response relationships.

There is a general paucity of data on estuarine invertebrates, this in turn, results in a lack of understanding in invertebrates' responses to changes in flow. There is a need for a regional investment in estuarine invertebrate research both in their taxonomy and in detailed research studies on driver-response relationships.

6.2.4 Incorporation of generic response curves in DRIFT

A 'tool' should be developed to assist ecologists in incorporating the generic estuarine indicator curves into the formats required by DRIFT, e.g. generic salinity curve be translated in a relationship for a site-specific baseline condition. In the short term, this can be done as a spreadsheet tool, but ultimately it should be incorporated into the DRIFT for ease of use.

7 REFERENCES

ABELL R, THIEME M, RICKETTS TH, OLWERO N, NG R, PETRY P, DINERSTEIN E, REVENGA C and HOEKSTRA J (2010) Concordance of freshwater and terrestrial biodiversity. *Conservation Letters* **4** (2) 127-136. DOI: https://conbio.onlinelibrary.wiley.com/doi/10.1111/j.1755-263X.2010.00153.x.

ABELL R, THIEME ML, REVENGA C, BRYER M, KOTTELAT M, BOGUTSKAYA N, COAD B, MANDRAK N, BALDERAS SC, BUSSING W, STIASSNY MLJ, SKELTON P, ALLEN GR, UNMACK P, NASEKA A, NG R, SINDORF N, ROBERTSON J, ARMIJO E, HIGGINS JV, HEIBEL TJ, WIKRAMANAYAKE E, OLSON D, LÓPEZ HL, REIS RE, LUNDBERG JG, PÉREZ MHS and PETRY P (2008) Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. *BioScience* **58** (5) 403-414. https://www.feow.org. (Accessed 8th November 2021).

ABRAMS M, CRIPPEN R and FUJISADA H (2020) ASTER global digital elevation model (GDEM) and ASTER global water body dataset (ASTWBD). *Remote Sensing* **12** (7) 1156.

ACREMAN MC, ARTHINGTON AH, COLLOFF MJ, COUCH C, CROSSMAN ND, DYER F, OVERTON I, POLLINO CA, STEWARDSON MJ and YOUNG W (2014a) Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. *Frontiers in Ecology and the Environment* **12** 466-473.

ACREMAN MC, OVERTON IC, KING J, WOOD PJ, COWX IG, DUNBAR MJ, KENDY E and YOUNG WJ (2014b) The changing role of eco-hydrological science in guiding environmental flows. *Hydrological Science Journal* **59** 433-450.

ADAME NS, SANTINI C, TOVILLA A, VÁZQUEZ-LULE X and CASTRO L (2015) Carbon stocks and soil sequestration rates of riverine mangroves and freshwater wetlands. *Biogeosciences Discuss*. **12** 1015-1045. www.biogeosciences-discuss.net/12/1015/2015/ doi:10.5194/bgd-12-1015-2015.

ADAMS JB and VAN NIEKERK L (2020) Ten Principles to Determine Environmental Flow Requirements for Temporarily Closed Estuaries. *Water* **12** 1944.

ADAMS JB, BATE GC, HARRISON TD, HUIZINGA P, TALJAARD S, VAN NIEKERK L, PLUMSTEAD EE, WHITFIELD AK and WOOLDRIDGE TH (2002) A method to assess the freshwater inflow requirements of estuaries and application to the Mtata estuary, South Africa. *Estuaries* **25** (6B) 1382-1393.

ADAMS JB, FERNANDES M and RIDDIN T (2019) *Chapter 5: Estuarine Habitat Extent and Trend,* VAN NIEKERK L, ADAMS JB, LAMBERTH SJ, MACKAY F, TALJAARD S, TURPIE JK, WEERTS S and RAIMONDO DC (eds.) (2019) South African National Biodiversity Assessment 2018: Technical Report, Volume 3: Estuarine Realm, Council for Scientific & Industrial Research (CSIR) report number CSIR/SPLA/EM/EXP/2019/0062/A, 52-75 pp, Report Number: SANBI/NAT/NBA2018/2019/Vol3/A, South African National Biodiversity Institute, Pretoria, South Africa.

ADAMS JB, VELDKORNET D and TABOT P (2016) Distribution of macrophyte species and habitats in South African estuaries. *South African Journal of Botany* **107** 5-11.

ADENEY RJ and HUGHES GM (1977) Some observations on the gills of the sunfish Mola mola. Journal of the Marine Biological Association of the United Kingdom **57** (3) 825-837.

ALDER J (2003) Putting the coast in the "Sea Around Us". The Sea Around Us Newsletter 15 1-2. URL: http://seaaroundus.org/newsletter/Issue15.pdf

ALEKSEEVSKIY NI, BERKOVICH KM and CHALOV RS (2008) Erosion, sediment transportation and accumulation in rivers. *International Journal of Sediment Research* **23** (2) 93-105.

ALLMENDINGER NE, PIZZUTO JE, POTTER JRN, JOHNSON TE and HESSION WC (2005) The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. *Geological Society of America Bulletin* **117** (1-2) 229-243.

ALSGTERHAG E and PETERSSON L (2004) Nutrient loading in the Kafue River between Mazabuka and Kafue Town, Zambia. Prepared by the Department of Environmental and Water Engineering, Uppsala University, Sweden, for the Ministry of Agriculture and Cooperatives, Zambia.

APPLETON CC (1977) The influence of temperature on the life-cycle and distribution of Biomphalaria pfeifferi (Krauss, 1948) in South-Eastern Africa. *International journal for parasitology* **7** (5) 335-345.

BARAS E and LUCAS MC (2001) Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *International Journal of Ecohydrology & Hydrobiology* **1** (3) 291-304.

BARBER-JAMES HM and LUGO-ORTIZ CR (2003) Ephemeroptera. In: de Moor IJ, Day JA and DE Moor FC (ed.). *Guides to the Freshwater Invertebrates of Southern Africa*. Volume 7: Insecta I. Ephemeroptera, Odonata and Plecoptera. WRC report No TT 207/03: 16-142. Water Research Commission, Pretoria.

BARBIER EB, HACKER SD, KENNEDY C, KOCH EW, STIER AC, SILLIMAN BR (2011) The value of estuarine and coastal ecosystem services. *Ecological Monographs* **81** (2) 169-193.

BASAGUREN AP, RIANO P and J POZO (2002) Life history patterns and dietary changes of several caddisfly (Trichoptera) species in a northern Spain stream. *Archiv für Hydrobiologie* **155** (1) 23-41.

BECK HE, ZIMMERMANN NE, McVICAR TR, VERGOPOLAN N, BERG A, WOOD EF (2018) Present and future Köppen-Geiger climate classification maps at 1 km resolution. *Scientific Data* **5** 180214, DOI https://goi.org/10.1038/sdata.2018.214.

BECK JS, THERON AT, KEMP A, HUIZINGA P AND BASSON GR (2004) Hydraulics of Estuarine Sediment Dynamics in South Africa – Implications for Estuarine Reserve Determination and the Development of Management Guidelines. WRC Report No 1257/1/04. Water Research Commission, Pretoria, South Africa.

BELGIU M (2015) UNIGIS International Association World Countries Boundaries. https://hub.arcgis.com/datasets/UIA::uia-world-countries-boundaries/about. (Accessed 18th August 2020).

BELL PR (1992) Green plants. Their origin and diversity. Dioscorides and Press, North America.

BELL-CROSS G and MINSHULL JL (1988) The fishes of Zimbabwe. National Museums and Monuments of Zimbabwe, Harare, Zimbabwe. 294 pp.

BEN-HAMADOU R, ATANASOVA N, and WOLANSKI E (2011) Chapter 10.13. Ecohydrology Modeling: Tools for Management. In: McLusky D and Wolanski E (ed.), *Treatise on Estuarine and Coastal Science*, Vol 10. Elsevier, Oxford. pp. 301-328.

BEST J (2019) Anthropogenic stresses on the world's big rivers. *Nature Geoscience* **12** (1) 7-21.

BIGGS BJF (1995) The contribution of disturbance, catchment geology and landuse to the habitat template of periphyton in stream ecosystems. *Freshwater Biology* **33** 419-438.

BIGGS BJF and THOMSEN HA (1995) Disturbance of stream periphyton by pertubations in shear stress: Time to structural failure and differences in community resistance. *Journal of Phycology* **31** 233-241.

BLAND LM, KEITH DA, MILLER RM, MURRAY NJ, RODRÍGUEZ JP (eds.) (2017a) Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria. Version 1.1. IUCN, Gland, Switzerland.

BOAR RR (2006) Responses of fringing *Cyperus papyrus* L. swamp to changes in water level. *Aquatic Botany* **84** 85-92.

BOKHUTLO T (2011) Life history and stock assessment of *Clarias gariepinus* In the Okavango Delta, Botswana. MSc thesis, Rhodes University. 135 p.

BORNETTE G and Puijalon S (2011) Response of aquatic plants to abiotic factors: a review. *Aquatic Science* **73** 1-4.

BOUHALA Z, MÁRQUEZ-Rodríguez J, CHAKRI K, SAMRAOUI F, EL-SEREHY HA, FERRERAS-ROMERO M and SAMRAOUI B (2020) The life history of the Ibero-Maghrebian endemic Oligoneuriopsis skhounate Dakki and Guidicelli (Ephemeroptera: Oligoneuriidae). *Limnologica* **81** 125761.

BOYD R, DALRYMPLE R and ZAITLIN BA (1992) Classification of clastic coastal depositional environments. *Sedimentary Geology* **80** 139-150.

BRACCIA A and VOSHELL JR (2006) Benthic Macroinvertebrate Responses to Increasing Levels of Cattle Grazing in Blue Ridge Mountain Streams, Virginia, USA. *Environ. Monit. Assess* **131** 185-200.

BREMNER JM, ROGERS J and WILLIS JP (1990) Sedimentological aspects of the 1988 Orange River floods. *Transactions of the Royal Society of South Africa* **47** 247-294.

BRIGHT C, MAGER S and HORTON S (2020) Response of nephelometric turbidity to hydrodynamic particle size of fine suspended sediment. *International Journal of Sediment Research* **35** (5) 444-454.

BROMILOW C (2010) Problem plants and alien weeds of South Africa. Briza Publications, South Africa.

BROWN C, JOUBERT A, BEUSTER H and GREYLING A (2013). DRIFT: DSS software development for integrated flow assessments. WRC Report No. 873/1/13. Water Research Commission, Pretoria.

BROWN C, JOUBERT A, TLOU T, BIRKHEAD A, MARNEWECK G, PAXTON B and SINGH A (2018) The Pongola Floodplain, South Africa – part 2: holistic environmental flows assessment. *Water SA* **44** (4) 746-759.

BROWN C, JOUBERT J, BIRKHEAD D, KOEHNKEN L, HOWARD G, REINECKE K, COWX I and SHERMAN P (2021) Comprehensive EFlows Assessment of the Lower Kafue Sub-catchment, Zambia. LKSC EFlows Final Report Series. Volume 2: Specialists' Report.

BRUTON MN (1979) The breeding biology and early development of *Clarias gariepinus* (Pisces: Clariidae) in Lake Sibaya, South Africa, with a review of breeding in species of the subgenus Clarias (Clarias). *The Transactions of the Zoological Society of London* **35** (1) 1-45.

BUDEBA YL and COWX IG (2007) The role of the freshwater shrimp Caridina nilotica (Roux) in the diet of the major commercial fish species in Lake Victoria, Tanzania. *Aquatic Ecosystem Health and Management* **10** (4) 368-380. DOI:10.1080/14634980701703876.

BURCHER CL and SMOCK LA (2002) Habitat distribution, dietary composition and life history characteristics of odonate nymphs in a blackwater coastal plain stream. *American Midland Naturalist* **148** 75-89.

BURNS A and WALKER KF (2000) Biofilms as food for decapods (Atyidae, Palaemonidae) in the river Murray, south Australia. *Hydrobiologia* **437** 83-90.

CABI (2023a) Commonwealth Agricultural Bureaux International, *Lagarosiphon illicifolius,* *https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.30548*, downloaded 27 April 2023.

CABI (2023b) Commonwealth Agricultural Bureaux International, *Phragmites australis* (Common reed), https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.40514, downloaded 27 April 2023.

COATES PALGRAVE K (1977) Trees of Southern Africa. C. Struik Publishers, Cape Town.

COLLOCOTT SJ, Vivier L and Cyrus DP (2014) Prawn community structure in the subtropical Mfolozi-Msunduzi estuarine system, Kwazulu-Natal, South Africa. *African Journal of Aquatic Science* **39** (2) 127-140.

CORBIN TA and GOONAN P (2010) Habitat and Water Quality Preferences of Mayflies and Stoneflies from South Australian Streams. *Transactions of the Royal Society of South Australia* **134** (1) 5-18. DOI:10.1080/3721426.2010.10887129.

COVICH AP (2010) Winning the biodiversity arms race among freshwater gastropods: competition and coexistence through shell variability and predator avoidance. *Hydrobiologia* 653 (**1**) 191-215.

CHAMBERS PA, PREPAS EE, HAMILTON HR and BOTHWELL ML (1991) Current velocity and its effect on aquatic macrophytes in flowing water. *Ecological applications* **1** 249-257.

DALLAIRE CO, LEHNER B, SAYRE R and THIEME M (2019) A multidisciplinary framework to derive global river reach classifications at high spatial resolution. *Environmental Research Letters* **14** (2) 024003.

DE MOOR F (1989) Alternative life-history styles in Simuliidae (Insecta, Diptera). In. Bruton MN (ed.) Alternative Life-History Styles of Animals. (pp.297-316). Edition: 1. Chapter: 14. Publisher: Kluwer Academic Publishers, Dordrecht.

DE MOOR FC and Scott KMF (2003) Guides to the Freshwater Invertebrates of Southern Africa, Volume 8: Hemiptera, Megaloptera, Neuroptera, Trichoptera and Lepidoptera. WRC Report No. TT 214/03. WRC Report No TT 214/03.

DE VILLIERS P and ELLENDER B (2008a) Status of the Orange-Vaal smallmouth yellowfish, Labeobarbus aeneus (Burchell 1822). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. pp: 76-91.

DE VILLIERS P and ELLENDER B (2008b) Status of the Orange-Vaal largemouth yellowfish, Labeobarbus kimberleyensis (Gilchrist and Thompson 1913). In: Impson ND, Bills IR, Wolhuter L. Technical Report on the State of Yellowfishes in South Africa. WRC Technical Report No. KV 212/08. Water Research Commission. Pretoria. ISBN: 978-1-77005-719-7. 92-102 pp.

DEPARTMENT of WATER AFFAIRS and FORESTRY (DWAF) (2008) Water resource protection and assessment policy implementation process. Resource Directed Measures for protection of water resource: Methodology for the determination of the ecological water requirements for estuaries. Department of Water Affairs and Forestry Version 2.1. Pretoria, South Africa.

DEPARTMENT OF WATER AND SANITATION (DWS) (2016a) Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to Umzimkulu WMA: Volume 4: Supporting Information on the Determination of Water Resource Classes – Economic Consequences of Operational Scenarios. DWS Report: RDM/WMA11/00/CON/CLA/0814.

DWS (2016b) Determination of Water Resources Classes and Resource Quality Objectives in the Breede-Gouritz Water Management Area: Linking the Value and Condition of the Water Resource. Report No: RDM/WMA8/00/CON/CLA/0616

DICKENS C, GRAHAM M, DE WINNAAR G, HODGSON K, TIBA F, SEKWELE R, SIKHAKHANE S, DE MOOR F, BARBER-JAMES H and VAN NIEKERK K (2008) The impacts of high winter flow releases from an impoundment on in-stream ecological processes. Report to the Water Research Commission. WRC Report No 1307/1/08. ISBN 978-1-77005-691-6. 187 pp.

DLA: CDSM (2006) Hydrological polygon and river line shapefiles mapped from the 1:50 000 topographical maps. Department of Land Affairs: Chief Directorate of Surveys and Mapping, South Africa, Cape Town.

DUMONT HJ (1994) The distribution and ecology of the fresh-and brackish-water medusae of the world. *Studies on the ecology of tropical zooplankton* 1-12.

DUVAIL S and HAMERLYNCK O (2003) Mitigation of negative ecological and socio-economic impacts of the Diama dam on the Senegal River Delta wetland Mauritania, using a model based decision support system. *Hydrology and Earth System Sciences* **7** 133-146.

EATON BC and LAPOINTE MF (2001) Effects of large floods on sediment transport and reach morphology in the cobble-bed Sainte Marguerite River. *Geomorphology* **40** (3-4) 291-309.

ECCLES DH (1986) Diet of the cyprinid fish Barbus aeneus (Burchell) in the PK le Roux Dam, South Africa, with special reference to the effect of turbidity on zooplanktivory. *African Zoology* **21** (3) 257-263.

ECKERT RA (2020) Leaf-associated periphyton in heterotrophic streams: Effect on macroinvertebrate assemblages and growth. PhD Thesis. University of Maryland, USA. 217 pp.

ELLENBROEK GA (1987) Ecology and productivity of an African wetland system: The Kafue Flats, Zambia. Dordrecht: Dr. W. Junk.

ELLERY K, ELLERY F (1997) Plants of the Okavango delta. A field guide. Tsaro publishers, Durban, South Africa.

ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE (ESRI) (1999-2017) ArcGIS 10.6. ESRI, California, United States of America.

ENGLUND G (1991) Effects of disturbance on stream moss and invertebrate community structure. *Journal of the North American Benthological Society* **10** 143-153.

ESRI (2013) World Cities. https://hub.arcgis.com/datasets/esri::world-cities. (Accessed 18th August 2020).

ESRI (2020) ArcGIS Pro 3.1 Environmental Systems Research Institute

EWART-SMITH JL (2013) The relationship between periphyton, flow and nutrients in foothill rivers of the south-western Cape, South Africa. Unpublished PhD thesis, University of Cape Town, Cape Town, South Africa.

FANSHAWE DB (1972) The biology of the reed – *Phragmites mauritianus* Kunth. *Kirkia* **8** (2) 147-150.

FEELY RA, ALIN SR, NEWTON J, SABINE CL, WARNER M, DEVOL A, KREMBS C and MALOY C (2010). The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science* **88** 442-449.

FISHBASE (2023a) Available at: https://www.fishbase.se/summary/9419 [Accessed June 1, 2023]

FISHBASE (2023b) Available at: https://www.fishbase.se/summary/1397 [Accessed June 1, 2023]

FRIBERG N and JACOBSEN D (1994) Feeding plasticity of two detritivore-shredders. *Freshwater Biology* **32** (1) 133-142.

FRONEMAN PW (2006) The population dynamics of the caridean shrimp, Palaemon peringueyi, in a small intermittently open Eastern Cape estuary. *African Journal of Aquatic Science* **31** 197-203.

FURSE MT, KIRK RC, MORGAN PR and TWEDDLE D (1979) Fishes: distribution and biology in relation to changes. In *Lake Chilwa: studies of change in a tropical ecosystem*. Springer Netherlands, Dordrecht. 175-208 pp.

GERBER A and GABRIEL MJM (2002) Aquatic invertebrates of South African rivers. A field guide. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

GLANSIS (2023) Great Lakes Aquatic Nonindigenous Species Information System, *Phragmites australis, https://nas.er.usgs.gov/queries/greatlakes/FactSheet.aspx?Species_ID=2937,* downloaded 27 April 2023.

GOUDIE A ed. (2004) Encyclopedia of geomorphology (Vol. 2). Psychology Press.

GRI (2016) GRI 305: Emissions (https://www.globalreporting.org/standards).

GRI (2018) GRI 303: Water and Effluents 2018 (https://www.globalreporting.org/standards).

GRI (2019) A Closer Look at Water and GHG Emissions Disclosure Mapping Reporting Practice to an Investor Perspective

GRILL G, LEHNER B, THIEME M, GEENEN B, TICKNER D, ANTONELLI F, BABU S, BORRELLI P, CHENG L, CROCHETIERE H, MACEDO HE, FILGUEIRAS R, GOICHOT M, HIGGINS J, HOGAN Z, LIP B, MCCLAIN ME, MENG J, MULLIGAN M, NILSSON C, OLDEN JD, OPPERMAN JJ, PETRY P,

LIERMANN CR, SÁENZ L, RODRÍGUEZ SS, SCHELLE P, SCHMITT RJP, SNIDER J, TAN F, TOCKNER K, VALDUJO PH, VAN SOESBERGEN A and ZARFL C (2019) Mapping the world's free-flowing rivers. *Nature* **569** (7755) 215-221.

GRIMM NB and FISHER SG (1989) Stability of periphyton and macroinvertebrates to disturbance by flash floods in a desert stream. *Journal of the North American Benthological Society* **8** 293-307.

GROVE R, CROKE J and THOMPSON C (2013) Quantifying different riverbank erosion processes during an extreme flood event. *Earth Surface Processes and Landforms* **38** (12) 1393-1406.

GIBBS RUSSEL GE, WATSON L, KOEKEMOER M, SMOOK L, BARKER NP, ANDERSON HM, DALLWITZ MJ (1990) Grasses of Southern Africa. Memoirs of the botanical survey of South Africa No. 38. National Botanical Gardens, Botanical Research Institute, South Africa.

GILLANDERS BM, and KINGSFORD MJ (2002) Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: An Annual Review* **40** 233-309.

GIRI C, OCHIENG E, TIESZEN LL, ZHU Z, SINGH A, LOVELAND T, MASEK J and DUKE N (2011) Status and distribution of mangrove forests of the world using earth observation satellite data (version 1.3, updated by UNEP-WCMC). *Global Ecology and Biogeography* **20** 154-159. DOI: 10.1111/j.1466-8238.2010.00584.x. Data URL: http://data.unep-wcmc.org/datasets/4.

HALE RL, COOK EM and BELTRÁN BJ (2019) Cultural ecosystem services provided by rivers across diverse social-ecological landscapes: A social media analysis. *Ecological Indicators* **107** 105580.

HARRISON TD and WHITFIELD AK (2006) Temperature and salinity as primary determinants influencing the biogeography of fishes in South African estuaries. *Estuarine, Coastal and Shelf Science* **66** (1-2) 335-345.

HART RC (1979) *The invertebrate communities: zooplankton, zoobenthos and littoral fauna* (Vol. 36). W. Junk, Hague. 108-161 pp.

HEEG J and BREEN CM (1982) Man and the Pongola floodplain. National Scientific Programmes Unit: CSIR, SANSP Report 56. 129 pp.

HICKIN EJ, eds. (1995) *River Geomorphology*. Wiley Press, Chichester.

HICKLEY P and BAILEY RG (1987) Food and feeding relationships of fish in the Sudd swamps (River Nile, southern Sudan). *Journal of Fish Biology* **30** (2) 147-159.

HILL WR (1996) Effects of light. In STEVENSON RH, Bothwell ML and LOWE RL (eds.). *Algal Ecology: Freshwater benthic ecosystems*. Academic Press, San Diego. 121-148 pp.

HILSENHOFF WL (2001) Diversity and classification of insects and collemola. In: THROP J. *Ecology and Classification of North American Freshwater Invertebrates* (Second Edition). Elsevier Science. ISBN: 9780126906479, 0126906475.

HOEINGHAUS DJ, WINEMILLER KO and BIRNBAUM JS (2007) Local and regional determinants of stream fish assemblage structure: inferences based on taxonomic vs. functional groups. *Journal of Biogeography* **34** (2) 324-338.

HOLOMUZKI JR and BIGGS BJF (2006) Food limitation affects algivory and grazer perfomance for New Zealand stream macroinvertebrates. *Hydrobiologia* **561** 83-94.

HOOKE JM (1979) An analysis of the processes of river bank erosion. *Journal of Hydrology* **42** (1-2) 39-62.

HOWARD G (2005) Invasions by plants in the inland waters and wetlands of Africa. Presentation given at the International Workshop on Biological Invasions of Inland Waters, Florence, Italy.

HOWARD J, HOYT S, ISENSEE K, TELSZEWSKI M and PIDGEON E (2014) Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.

HUDSON PF (2003) Event sequence and sediment exhaustion in the lower Panuco Basin, Mexico. *Catena* **52** (1) 57-76.

HUGGETT R and SHUTTLEWORTH E (2022) *Fundamentals of geomorphology*. Taylor and Francis.

HUGGINS DG and DUBOIS MB (1982) Factors affecting micro distribution of two species of burrowing dragonfly larvae with notes on their biology (Anisoptera: Gomphidae). *Odonatologica* **11** (1) 1-14.

HUTCHISON J, MANICA A, SWETNAM R, BALMFORD A and SPALDING M (2014) Predicting global patterns in mangrove forest biomass. *Conservation Letters* **7** (3) 233-240. DOI: 10.1111/conl.12060

JÄCH MA and BALKE M (2008) Global diversity of water beetles (Coleoptera) in freshwater. *Hydrobiologia* **595** 419-442.

JARVIS A, REUTER HI, NELSON A and GUEVARA E (2008) Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database. https://srtm.csi.cgiar.org. (Accessed 8th November 2021).

JOUBERT AR, BROWN C, KING JM, BEUSTER H and GREYLING A (2022). DRIFT: Incorporating an eco-social system network and time-series approach into environmental flow assessments. *African journal of Aquatic Sciences* **47** (3) 338-352.

JUNEAU KJ, TARASOFF CS (2013) The seasonality of survival and subsequent growth of common reed (*Phragmites australis*). Rhizome fragments. *Invasive Plant Science Management* **6** (1) 79-86.

JUNK WJ, BAYLEY PB and SPARKS RE (1989) The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences* **106** (1) 110-127.

KEITH DA, FERRER-PARIS JR, NICHOLSON E, KINGSFORD RT (eds.) (2020) The IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups. IUCN, Gland, Switzerland. ISBN: 978-2-8317-2077-7. DOI:10.2305/IUCN.CH.2020.13.en.

KEITH DA, RODRÍGUEZ JP, RODRÍGUEZ-CLARK KM, NICHOLSON E, AAPALA K, ALONSO A, ASMUSSEN M, BACHMAN S, BASSET A, BARROW EG, BENSON JS, BISHOP MJ, BONIFACIO R, BROOKS TM, BURGMAN MA, COMER P, COMÍN FA, ESSL F, FABER-LANGENDOEN D, FAIRWEATHER PG, HOLDAWAY RJ, JENNINGS M, KINGSFORD RT, LESTER RE, NALLY RM, MCCARTHY MA, MOAT J, OLIVEIRA-MIRANDA MA, PISANU P, POULIN B, REGAN TJ, RIECKEN U, SPALDING MD, ZAMBRANO-MARTÍNEZ S (2013) Scientific Foundations for an IUCN Red List of Ecosystems. *PLoS ONE* **8** e62111.

KING J and PALMER C (2022) Perspectives on Protecting African freshwater Ecosystems in the Anthropocene. *African Journal of Aquatic Science **47*** (3) iii-vi.

KING J, BEUSTER H, BROWN, C and JOUBERT A (2014) Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system. *Hydrological Sciences Journal*. DOI: 10.1080/02626667.2014.888069.

KING JM, BROWN CA and SABET H (2003) A scenario-based holistic approach to environmental flow assessments for regulated rivers. *Rivers Research and Applications* **19** (5-6) 619-640.

KLEYNHANS CJ, THIRION C and MOOLMAN J (2005) A Level I Ecoregion classification system for South Africa, Lesotho and Swaziland. Resource Quality Services, Department of Water Affairs and Forestry, Private Bag X313, Pretoria, 0001, South Africa.

KOLDING J and VAN ZWIETEN PA (2012) Relative Lake level fluctuations and their influence on productivity and resilience in tropical lakes and reservoirs. *Fisheries Research* **115** 99-109.

KOTSCHY K and ROGERS K (2008) Reed clonal characteristics and response to disturbance in a semi-arid river. *Aquatic Botany* **88** 47-56.

KOTSCHY KA, ROGERS KH and CARTER AJ (2000) Patterns of change in reed cover and distribution in a seasonal riverine wetland in South Africa. *Folia geobotanica* **35** (4) 363-373.

KUHNLE RA, BINGNER RL, FOSTER GR and GRISSINGER EH (1996) Effect of land use changes on sediment transport in Goodwin Creek. *Water Resources Research* **32** (10) 3189-3196.

LAMBERTH SJ and TURPIE JK (2003) The role of estuaries in South African fisheries: economic importance and management implications. *African Journal of Marine Science* **25** 131-157.

LAMBERTH SJ, DRAPEAU L and BRANCH GM (2009) The effects of altered freshwater inflows on catch rates of non-estuarine-dependent fish in a multispecies nearshore line-fishery. *Estuarine, Coastal and Shelf Science* **84** 527-538.

LAURENT A, FENNEL K, CAI WC, HUANG WH, BARBERO L and WANNINKHOF AR (2017) Eutrophication induced acidification of coastal waters in the northern Gulf of Mexico: Insights into origin and processes from a coupled physical-biogeochemical model. *Geophysical Research Letters* **44** 946-956**.**

LEHNER B and DÖLL P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* **296** (1-4) 1-22. https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database. (Accessed 8th November 2021).

LEHNER B, LIERMANN CR, REVENGA C, VÖRÖSMARTY C, FEKETE B, CROUZET P, DÖLL P, ENDEJAN M, FRENKEN K, MAGOME J, NILSSON C, ROBERTSON JC, RÖDEL R, SINDORF N and WISSER D (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment* **9** (9) 494-502. http://globaldamwatch.org/data/#core_global. (Accessed 8th November 2021).

LEHNER B, VERDIN K, and JARVIS A (2008) New global hydrography derived from spaceborne elevation data. *Eos Transactions American Geophysical Union* **89** (10) 93-94. https://www.hydrosheds.org/page/availability. (Accessed 8th November 2021).

LINKE S, LEHNER B, DALLAIRE CO, ARIWI J, GRILL G, ANAND M, BEAMES P, LEVINE VB, MAXWELL S, MOIDU H, TAN F and THIEME M (2019) Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Scientific Data* **6** (1) 1-15. https://www.hydrosheds.org/page/overview. (Accessed 8th November 2021).

LINKE S, LEHNER B, OUELLET DALLAIRE C, Ariwi J, Grill G, ANAND M, BEAMES P, BURCHARD-LEVINE V, MAXWELL S, MOIDU H and TAN F (2019) Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Scientific data* **6** (1) 283.

LING SW (1969) The general biology and development of *Macrobrachium rosenbergii* (de Man). *FAO Fisheries Report*. **57** (3) 589-606.

LISLE TE and HILTON S (1992) The Volume of Fine Sediment. In Pools: An Index of Sediment Supply In Gravel-Bed Streams 1. *JAWRA Journal of the American Water Resources Association* **28** (2) 371-383.

MACKAY RJ (1984) Life history patterns of Hydropsyche bronta and H. morose (Trichoptera: Hydropsychidae) in summer-warm rivers of southern Ontario. *Canadian Journal of Zoology* **62** (2) 271-275.

MACROINVERTEBRATES.ORG (2023) Available at https://www.macroinvertebrates.org/taxa-info/plecoptera-larva/perlidae Accessed on 5 May 2023.

MACUIANE MA, KAUNDA EK, JAMU DM and KANYERERE GZ (2009) Reproductive biology and breeding of Barbus paludinosus and B. trimaculatus (Teleostei: Cyprinidae) in Lake Chilwa, Malawi: implications for fisheries management. *African Journal of Aquatic Science* **34** (2) 123-130.

MACHENA C, KAUTSKY N and LINDMARK G (1990) Growth and reproduction of *Lagarosiphon ilicifolius* in Lake Kariba – a man-made tropical lake. *Aquatic Botany* **37** 1-15.

MARRIOTT SP (1997) Fisheries institutional reform in developing countries. *Marine Policy* **21** (5) 435-444.

MAYER M and LIKENS G (1987) The Importance of algae in a shaded headwater stream as food for an abundant caddisfly (Trichoptera). *Freshwater Science* **6** (4) 262-269.

MCNAIR JN, NEWBOLD JD and HART DD (1997) Turbulent transport of suspended particles and dispersing benthic organisms: how long to hit bottom? *Journal of Theoretical Biology* **188** (1) 29-52.

MCOWEN C, WEATHERDON LV, BOCHOVE J, SULLIVAN E, BLYTH S, ZOCKLER C, STANWELL-SMITH D, KINGSTON N, MARTIN CS, SPALDING M, and FLETCHER S (2017). A global map of saltmarshes (v6.1). *Biodiversity Data Journal* (5) e11764. https://doi.org/10.3897/BDJ.5.e11764. Data: https://doi.org/10.34892/07vk-ws51

MCSWEENEY SL, KENNEDY DM, RUTHERFURD ID and STOUT JC (2017) Intermittently Closed/Open Lakes and Lagoons: Their global distribution and boundary conditions. *Geomorphology* **292** 142-152.

MERRON GS and MANN BQ (1995) The reproductive and feeding biology of *Schilbe intermedius* Rüppell in the Okavango Delta, Botswana. *Hydrobiologia* **308** (2) 121-129.

MERRON GS, and BRUTON MN (1988) The ecology and management of the fishes of the Okavango Delta, Botswana, with special reference to the role of the seasonal floods. *JLB Smith Institute of Ichthyology Investigational Report **29*** 1-291.

MESSAGER ML, LEHNER B, COCKBURN C, LAMOUROUX N, PELLA H, SNELDER T, TOCKNER K, TRAUTMANN T, WATT C and DATRY T (2021) Global prevalence of non-perennial rivers and streams. *Nature* **594** (7863) 391-397.

MESSAGER ML, LEHNER B, GRILL G, NEDEVA I and SCHMITT O (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature communications* **7** (1) 13603.

MILER O, ALBAYRAK I, NIKORA V and O'HARE M (2012) Biochemical properties of aquatic plants and their effects on plant-flow interactions in streams and rivers. *Aquatic Sciences* **74** 31-44.

MOOLMAN J (2008) River long profiles aid in ecological planning. PositionIT Jan/Feb 3-45.

MOSLEY L, ZAMMIT B, JOLLEY A and BARNETT L (2014) Acidification of lake water due to drought. *Journal of Hydrology*. **511** 484-493.

MRC (Mekong River Commission). 2017. The Council Study: Study on the sustainable management and development of the Mekong River, including impacts of mainstream hydropower projects. BioRA Final Technical Report Series. Volume 4: Assessment of Planned Development Scenarios. FINAL REPORT. Vientiane, Lao PDR. 145 pp.

MUDAU C (2006) *Cynodon dactylon*. PlantZAfrica.com. South African National Botanical Institute. http://pza.sanbi.org/cynodon-dactylon. Downloaded on 27.09.22.

MULLIGAN M, VAN SOESBERGEN A and SÁENZ L (2020). GOODD, a global dataset of more than 38,000 georeferenced dams. *Scientific Data* **7** (1) 1-8. http://globaldamwatch.org/data/#core_global. (Accessed 8th November 2021).

NAIDOO G (2020) Waterlogging tolerance of the common reeds *Phragmites mauritianus* and *P. australis. African Journal of Ecology* **59** (4) 1004-1012.

NATIONAL BIODIVERSITY ASSESSMENT (2018) Technical Report, Version 3, Council for Scientific and Industrial Research (CSIR) and South African National Biodiversity Institute (SANBI), Pretoria, South Africa. CSIR report number CSIR/NRE/ECOS/IR/2018/0001/A; SANBI report number http://hdl.handle.net/20.500.12143/5847

NEL JL, DRIVER AL, STRYDOM WF, MAHERRY AM, PETERSEN C, HILL L, ROUX DJ, NIENABER S, VAN DEVENTER H, SWARTZ ER, SMITH-ADAO LB (2011a) Atlas of Freshwater Ecosystem Priority Areas in South Africa: Maps to support sustainable development of water resources. Water Research Commission Report No. K5/1801, WRC, Pretoria, South Africa.

NEL JL, MURRAY KM, MAHERRY AM, PETERSEN CP, ROUX DJ, DRIVER A, HILL L, VAN DEVENTER H, FUNKE N, SWARTZ ER, SMITH-ADAO LB, MBONA N, DOWNSBOROUGH L, NIENABER S (2011b)

Technical Report: National Freshwater Ecosystem Priority Areas project. Water Research Commission (WRC) Report No. 1801/2/11, WRC, Pretoria, South Africa.

NEP-WCMC and SHORT FT (2021). Global distribution of seagrasses (version 7.1). Seventh update to the data layer used in Green and Short (2003). Cambridge (UK): UN Environment World Conservation Monitoring Centre. Data DOI: https://doi.org/10.34892/x6r3-d211.

NICHOLAS AP and WALLING DE (1996) The significance of particle aggregation in the overbank deposition of suspended sediment on river floodplains. *Journal of Hydrology* **186** (1-4) 275-293.

NOVELO-GUTIÉRREZ R, RAMÍREZ A and GONZÁLEZ-SORIANO E (2018) Superfamily Gomphoidea. In *Thorp and Covich's Freshwater Invertebrates*. Academic Press. 377-397 pp

NGUGI CC, MANYALA JO, NJIRU M and MLEWA CM. 2009. Some aspects of the biology of the stargazer mountain catfish, *Amphilius uranoscopus* (pfeffer); (Siluriformes: Amphiliidae) indigenous to Kenya streams. *African Journal of Ecology* **47** (4) 606-613.

OKEYO DO (1998) Updating names, distribution and ecology of riverine fish of Kenya in the Athi-Galana-Sabaki River drainage system. Naga, ICLARM Q **21** (1) 44-53.

OLLIS DJ, EWART-SMITH JL, DAY JA, JOB NM, MACFARLANE DM, SNADDON CD, SIEBEN EJJ, DINI JA and MBONA N (2015) The development of a classification system for inland aquatic ecosystems in South Africa. *Water SA* **41** (5) 727-745.

OLLIS DJ, SNADDON CD, JOB NM and MBONA N (2013) Classification System for wetlands and other aquatic ecosystems in South Africa. User Manual: Inland Systems, South African National Biodiversity Institute (SANBI) *Biodiversity Series 22*. SANBI, Pretoria, South Africa.

OMARJEE A, TALJAARD S, RAMJUKADH C-L and VAN NIEKERK L (2021) pH variability in catchment flows to estuaries – a South African perspective. *Estuarine, Coastal and Shelf Science* **262** (5) 107605.

OMARJEE A, TALJAARD S, WEERTS SP and ADAMS JB (2020) The influence of mouth status on pH variability in small temporarily closed estuaries. Estuarine Coastal and Shelf Science **246** 107043.

OSORIO JHM, POLLIO A, FRUNZO L, LENS PNL, ESPOSITO G (2021) A review of microalgal biofilm technologies: definition, applications, settings and analysis. *Frontiers in Chemical Engineering* **3** 1-23.

PBWO/IUCN 2009. Final Scenario Report: Report 4: Pangani River Basin Flow Assessment, Moshi, 23 pp.

PEEL RA (2012) The biology and abundance of three Cichlid species from the Kavango and Caprivi regions, Namibia (Doctoral dissertation). University of Namibia, Namibia

PEIPOCH M and VALETT H (2019) Trophic interactions among algal blooms, macroinvertebrates, and brown trout: Implications for trout recovery in a restored river. *River Research and Application* **35** (9) 1563-1574.

PEKEL JF, COTTAM A, GORELICK N and BELWARD AS (2016) High-resolution mapping of global surface water and its long-term changes. *Nature* **540** (7633) 418-422.

PERÁN J, VELASCO J and MILLÁN A (1999) Life history and secondary production of Caenis luctuosa (Ephemeroptera) in a semi arid stream (Southeast Spain). *Hydrobiologia* **400** 187-194.

PETERSON, C.G., BOULTON, A.L. 1999. Stream permanence influences microalgal food availability to grazing tadpoles in arid-zone springs. *Oecologia* 118:340-352.

PLANTZAFRICA (2023a) *Salix mucronata,* http://pza.sanbi.org/salix-mucronata, downloaded 28 April 2023.

PLANTZAFRICA (2023b) *Phragmites australis, https://pza.sanbi.org/phragmites-australis*, downloaded 27 April 2023.

POTTS WM, GÖTZ A and JAMES N (2015) Review of the projected impacts of climate change on coastal fishes in southern Africa. *Reviews in Fish Biology and Fisheries* **25** (4) 603-630.

POWER ME, MATTHEWS WJ (1983) Algae-grazing minnows (*Campostoma anomalum*), piscivorous bass (*Micropterus* spp.) and the distribution of attached algae in a small prairie-margin stream. *Oecologia* **60** 328-332.

PRINGLE CM, BLAKE GA, COVICH AP, BUZBY M and FINLEY A (1993) Effects of omnivorous shrimp in a montane tropical stream: sediment removal, disturbance of sessile invertebrates and enhancement of understory algal biomass. *Oecologia* **93** 1-11.

PRITCHARD DW (1952). Salinity distribution and circulation in the Chesapeake Bay estuarine system. *Journal Marine Research* **11** 106-123.

PHIRI C, CHAKONA A, DAY JA (2012) Macroinvertebrates associated with two submerged macrophytes, *Lagarosiphon ilicifolius* and *Vallisineria aethiopica*, in the Sanyati Basin, Lake Kariba, Zimbabwe: effect of plant morphological complexity. *African Journal of Aquatic Science* **37** (3) 277-288.

QUAYLE LM, APPLETON CC and DICKENS CWS (2010) The effects of stream flow manipulation on the invertebrate hosts of malaria, bilharzia and liver fluke disease. Report to the Water Research Commission by Institute of Natural Resources WRC Report No. TT 456/10.

RACTLIFFE G and DALLAS H (2005) Specialist Report: Macroinvertebrates. In: *Riverine RDM Report*. Volume 1: Specialist Reference Report. Olifants Doring Catchment Ecological Water Requirements Study. BIRKHEAD A, BOUCHER C, BROWN C, DOLLAR E, HARDING W, KAMISH W, PAXTON B, PEMBERTON C, RACTLIFFE S (eds). Unpublished DWAF Report. Project No: 2002-376. 308 pp.

RATCLIFFE S (2009) Disturbance and temporal variability in invertebrate assemblages in two South African rivers. PhD Thesis. University of Cape Town.

REID GM (1985) A revision of African species of Labeo (Pisces: Cyprinidae) and a re-definition of the genus. Verlag von J. Cramer, Braunschweig. (Ref. 1440) 322 pp.

REINECKE MK (2013) Links between lateral riparian vegetation zones and flow. Unpublished PhD thesis, University of Stellenbosch, Stellenbosch, South Africa.

REMSBURG A (2011) Relative influence of prior life stages and habitat variables on dragonfly (Odonata: Gomphidae) densities among lake sites. *Diversity* **3** (2) 200-216.

RIVERS-MOORE NA and FC DE MOOR (2008) Impact of winter flow regulation on pest-level populations of blackfly (Diptera: Simuliidae) and non-target faunal communities in a South African river. *African Journal of Aquatic Science* **33** (2) 125-134.

RODRIGUEZ JP, KEITH DA, RODRIGUEZ-CLARK KM, MURRAY NJ, NICHOLSON E, REGAN TJ, MILLER RM, BARROW EG, BLAND LM, BOE K, BROOKS TM, OLIVEIRA-MIRANDA MA, SPALDING M and WIT P (2015) A practical guide to the application of the IUCN Red List of Ecosystems criteria. *Philosophical Transactions of the Royal Society B: Biological Sciences* **370** (1662) 20140003.

RODRÍGUEZ JP, RODRÍGUEZ-CLARK KM, BAILLIE JEM, ASH N, BENSON J, BOUCHER T, BROWN C, BURGESS ND, COLLEN B, JENNINGS M, KEITH DA, NICHOLSON E, REVENGA C, REYERS B, ROUGET M, SMITH T, SPALDING M, TABER A, WALPOLE M, ZAGER I and ZAMIN T (2011) Establishing IUCN Red List Criteria for Threatened Ecosystems. *Conservation Biology* **25** (1) 21-29.

ROMINGER JT, LIGHTBODY AF and NEPF HM (2010) Effects of Added Vegetation on Sand Bar Stability and Stream Hydrodynamics. *Journal of Hydraulic Engineering* **136** (12) 994-1002.

ROSEMOND AD, MULHOLLAND PJ, ELWOOD JW (1993) Top-down and bottom-up control of stream periphyton: effects of nutrients and herbivores. *Ecology* **74** (4) 1264-1280.

ROWNTREE JM and WADESON RA (1999) A hierarchical geomorphological model for the classification of selected South African rivers. Water Research Commission (WRC) Report No. 497/1/99. WRC, Pretoria, South Africa.

ROWNTREE JM, WADESON RA and O'KEEFE J (2000) The development of a geomorphological classification system for the longitudinal zonation of South African rivers. *South African Geographical Journal* **82** (3) 163-172. https://doi.org/10.1080/03736245.2000.9713710.

ROWNTREE KM. and Dollar ES (1999) Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group* **24** (2) 127-134.

SANBI (2023a) Available at: http://speciesstatus.sanbi.org/taxa/detail/183/ [Accessed June 1, 2023]

SANBI (2023b) Available at: http://speciesstatus.sanbi.org/assessment/last-assessment/158/ [Accessed June 1, 2023]

SARTORI M and BRITTAIN JE (2003) Ephemeroptera. In: RESH VH and CARDE RT (eds). *Encyclopaedia of Insects*, Academic Press, Amsterdam, 373-380.

SCOTT KMF (1988) Twenty-five years of Trichoptera research relating to Southern Africa-a personal view. *Journal of the Limnological Society of Southern Africa* **14** (1) 16-23.

SEEGERS L (2008) The fishes collected by GA Fischer in East Africa in 1883 and 1885/86. *Zoosystematics and Evolution* **84** (2) 149-195.

SEEGERS L, DE VOS L and OKEYO DO (2003) Annotated checklist of the freshwater fishes of Kenya (excluding the lacustrine haplochromines from Lake Victoria). *Journal of East African Natural History*. **92** (1) 11-47.

SENNATT KM, SALANT NL, RENSHAW CE and MAGILLIGAN FJ (2006) Assessment of methods for measuring embeddedness: application to sedimentation in flow regulated STREAMS1. *Journal of the American Water Resources Association* **42** (6) 1671-1682.

SIIKAMÄKI J, SANCHIRICO JN, JARDINE S, MCLAUGHLIN D and MORRIS DF (2012) Blue Carbon: Global options for reducing emissions from the degradation and development of coastal ecosystems. Resources for the Future, Washington.

SIVARUBAN T, BARATHY S, VENKATARAMAN K and ARUNACHALAM M (2010) Life cycle studies of Heptageniidae (Insecta Ephemeroptera) in Kumbbakarai Stream of Western Ghats, Tamil Nadu, India. *Journal of Threatened Taxa* **2** (10) 1223-1226.

SKELTON P (1995) A *Complete Guide to the Freshwater Fishes of Southern Africa*. Southern Book Publishers. ISBN 1-86812-350-2.

SKELTON P (2001) *A Complete Guide to the Freshwater Fishes of Southern Africa*.

SMITH SL (2023) Estimating Embeddedness from Bankfull Shear Velocity in Gravel Streambeds to Assess Sediment Impacts on Aquatic Biota, PhD, Virginia Tech.

SMITH-ADAO L, PETERSEN C, NEL J, SILBERBAUER M, SCHERMAN P AND GRENFELL M (2018) Chapter 2: Origin, development and improvement of the rivers dataset. In: Volume 2a: South African Inventory of Inland Aquatic Ecosystems, VAN DEVENTER et al. South African National Biodiversity Assessment 2018 Technical Report, Version 3, Council for Scientific and Industrial Research (CSIR) and South African National Biodiversity Institute (SANBI), Pretoria, South Africa. CSIR report number CSIR/NRE/ECOS/IR/2018/0001/A; SANBI report number http://hdl.handle.net/20.500.12143/5847.

SOUTHARD J (2006) 12.090 Introduction to Fluid Motions, Sediment Transport, and Current-Generated Sedimentary Structures, Course Textbook. In MIT Open Courseware: Massachusetts Institute of Technology.

SOUTHERN WATERS (2021) Comprehensive EFlows Assessment of the Lower Kafue Sub-catchment, Zambia. LKSC EFLOWS FINAL REPORT SERIES. VOLUME 2: SPECIALISTS' REPORT

SPALDING MD, BLASCO F and FIELD CD (Eds.) (1997) World mangrove atlas. Okinawa (Japan): International Society for Mangrove Ecosystems. 178 pp. Compiled by UNEP-WCMC, in collaboration with the International Society for Mangrove Ecosystems (ISME). Version 3. URL:

https://archive.org/details/worldmangroveatl97spal. Data URL: http://data.unep-wcmc.org/datasets/6.

SPALDING MD, KAINUMA M, and COLLINS L. (2010) World atlas of mangroves. A collaborative project of ITTO, ISME, FAO, UNEP-WCMC, UNESCO-MAB, UNU-INWEH, and TNC. London (UK): Earthscan, London. 319 pp. URL: http://data.unep-wcmc.org/datasets/5.UNEP-WCMC

STEIN ED, GEE E, ADAMS JB, IRVING K and VAN NIEKERK L (2021) Advancing the Science of Environmental Flows for Protection of Coastal Estuaries and Lagoons. *Water* **13** (5) 595 https://doi.org/10.3390/w13050595.

STEINMAN AD, MULHOLLAND JP and KIRSCHTEL D (1991) Interactive effects of nutrient reduction and herbivory on biomass, taxonomic structure and P uptake in lotic periphyton communities. *Canadian Journal of Fisheries and Aquatic Sciences* **48** (10) 1951-1959.

SULLIVAN PR and WOOD R (2012) Water Hyacinth (*Eichhornia crassipes* (Mart.) Solms) seed longevity and the implications for management. 18th Australasian Weeds Conference, Melbourne.

SUREN AM and DUNCAN MJ (1999) Rolling stones and mosses: effect of substrate stability on bryophyte communities in streams. *Journal of the North American Benthological Society* **18** (4) 457-467.

TAKAKU J, TADONO T and TSUTSUI K (2014) Generation of high resolution global DSM from ALOS PRISM. In: ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences, ISPRS Technical Commission IV Symposium, 14-16 May 2014, Suzhou, China, XL (4) 243-248. DOI: https://doi.org/10.5194/isprsarchives-XL-4-243-2014.

TAKAKU J, TADONO T, DOUTSU M, OHGUSHI F and KAI H (2020) Updates of 'AW3D30'ALOS Global Digital Surface Model with other Open Access datasets. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* **43** 183-189. https://search.asf.alaska.edu/#/. (Accessed 8th November 2021).

TALJAARD S, VAN NIEKERK L and JOUBERT W (2009) Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: Southern hemisphere perspective. *Estuarine, Coastal and Shelf Science* **85** (3) 407-421.

TONKIN JD, POFF NL, BOND NR, HORNE A, MERRITT DM, REYNOLDS LV, OLDEN JD, RUHI A and LYTLE DA (2019) Prepare river ecosystems for an uncertain future. *Nature* **570** (7761) 301-303.

TSELIOU F and TSELEPIDES A (2020). The importance of the ecosystem approach in the management of the marine environment. *Euro-Mediterranean Journal for Environmental Integration* **5** (2) 1-5.

TWEDDLE D, COWX IG, PEEL RA and WEYL OLF (2015) Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. *Fisheries Management and Ecology* **22** (1) 99-111.

THE 2 HR AQUARIST (2023) Nutrient uptake through leaves? https://www.2hraquarist.com/blogs/hot-topics/nutrient-uptake-through-leaves, downloaded 26 April 2023.

THIRION C (2007) Module E: Macroinvertebrate Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (version 2). Joint Water Research Commission and Department of Water Affairs and Forestry report.

THIRION C (2016) The determination of flow and habitat requirements for selected riverine macroinvertebrates. Doctoral dissertation, North-West University, Potchefstroom Campus, South Africa.

TRUHLAR JF (1978) Determining suspended sediment loads from turbidity records. *Hydrological Sciences Journal* **23** (4) 409-417.

UN ENVIRONMENT WORLD CONSERVATION MONITORING CENTRE (UNEP-WCMC) (2013). Global distribution of saltmarsh (ver. 1.0). Unpublished dataset. Cambridge (UK): UNEP World Conservation Monitoring Centre.

UN *et al.* (2014b) System of Environmental-Economic Accounting 2012: Experimental Ecosystem Accounting. United Nations, New York City.

UNDP-GEF ORANGE-SENQU STRATEGIC ACTION PROGRAMME (2013) EFR Monitoring Programme. Research Project on Environmental Flow Requirements of the Fish River and the Orange-Senqu River Mouth.

UNEP-NAIROBI CONVENTION/WIOMSA (2020) Guidelines on Environmental Flows (EFlows) Assessments for the Western Indian Ocean (WIO) region. UNEP, Nairobi. Compiled and prepared by: BROWN C and KING J, with contributions from VAN NIEKERK L and TALJAARD S. 79 pp.

UNITED NATIONS (1998) United Nations Framework Convention on Climate Change (UNFCCC) Bonn 1998.

UNITED NATIONS (2017) SEEA Experimental Ecosystem Accounting: Technical Recommendations. Final Draft V3.2: 16 October 2017, prepared as part of the joint UNEP / UNSD / CBD project on Advancing Natural Capital Accounting funded by NORAD.

UNITED NATIONS ENVIRONMENT WORLD CONSERVATION MONITORING CENTRE (UNEP-WCMC), Conservation International, and The Nature Conservancy (2016) Global distribution of saltmarsh (ver. 4.0). Cambridge (UK): UNEP World Conservation Monitoring Centre. URL: http://data.unep-wcmc.org/

UNITED NATIONS, EUROPEAN UNION, FOOD and AGRICULTURAL ORGANISATION of the UNITED NATIONS, INTERNATIONAL MONITORY FUND, ORGANISATION for ECONOMIC CO-OPERATION and DEVELOPMENT BANK (UN *et al.*) (2014a) System of Environmental-Economic Accounting 2012: Central Framework. United Nations, New York City.

UNITED STATES GEOLOGICAL SURVEY (USGS) (2020) USGS EROS Archive – Digital Elevation – Shuttle Radar Topography Mission Water Body Dataset. https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-water-body (Accessed 11th November 2021).

USEFUL TEMPERATE PLANTS DATABASE (2022) Cynodon dactylon. Creative Commons Attribution-Non-Commercial Share Alike 3.0 Unreported License. https://temperate.theferns.info/plant/Cynodon+dactylon. Downloaded on 27.09.22.

USEPA (2003) The biological effects of Suspended and Bedded Sediment (SABS) in aquatic systems: A Review Internal Report; United States Environmental Protection Agency.

VAN COLLER ALAN, ROGERS K and HERITAGE G (1997) Linking riparian vegetation types and fluvial geomorphology along the Sabie River within the Kruger National Park, South Africa. *African Journal of Ecology* **35** (3) 194-212.

VAN DER WAAL BCW (1980) Aspects of the fisheries of Lake Liambezi, Caprivi. Journal of the Limnological Society of southern Africa, **6** (1) 19-31.

VAN DER WAAL BCW (1996) Some observations on fish migrations in Caprivi, Namibia. *Southern African Journal of Aquatic Science* **22** (1-2) 62-80 pp.

VAN DEVENTER H, SMITH-ADAO L, COLLINS NB, GRENFELL M, GRUNDLING A, GRUNDLING P-L, IMPSON D, JOB N, LÖTTER M, OLLIS D, PETERSEON C, SCHERMAN P, SIEBEN EJJ, SNADDON K, TERERAI F and VAN DER COLFF D (2019) South African National Biodiversity Assessment 2018: Technical Report. Volume 2: Inland Aquatic (Freshwater) Component. Council for Scientific and Industrial Research (CSIR) and South African National Biodiversity Institute (SANBI), Pretoria, South Africa. CSIR report number CSIR/NRE/ECOS/IR/2019/0004/A. SANBI handle: http://hdl.handle.net/20.500.12143/6230.

VAN DEVENTER H, VAN NIEKERK L, ADAMS J, DINALA MK, GANGAT R, LAMBERTH SJ, LÖTTER M, MBONA N, MACKAY F, NEL JL, RAMJUKADH C-L, SKOWNO A and WEERTS SP (2020) National Wetland Map 5 – An improved spatial extent and representation of inland aquatic and estuarine ecosystems in South Africa. Water SA, 46 (1) 66-79. https://doi.org/10.17159/wsa/2020.v46.i1.7887.

VAN GINKEL CE, GLEN RP, GORDON-GRAY KD, CILLIERS CJ, MUASYA M and VAN DEVENTER PP (2010) Easy identification of some South African Wetland Plants (grasses, restios, sedges, rushes, bulrushes, eriocaulons and yellow eyed grasses). Water Research Commission Report TT 479/10, Water Research Commission, Pretoria, South Africa. 390 pp.

VAN NIEKERK L and TALJAARD S (2023) Southern African Estuaries: Physical states associated with estuarine ecosystem types and application in E-flow studies. CSIR Report. Stellenbosch, South Africa.

VAN NIEKERK L TALJAARD S, ADAMS JB, LAMBERTH SJ, HUIZINGA P, TURPIE JK and WOOLDRIDGE TH (2019a) An environmental flow determination method for integrating multiple-scale ecohydrological and complex ecosystem processes in estuaries. *Science of the Total Environment* **656** (15) 482-494.

VAN NIEKERK L, ADAMS JB, ALLEN D, TALJAARD S, WEERTS S, LOUW D, TALANDA C and VAN ROOYEN P (2019b) Assessing and planning future estuarine resource use: A scenario-based regional scale freshwater allocation approach. *Science of the Total Environment* **657** (20) 1000-1013.

VAN NIEKERK L, ADAMS JB, BATE GC, FORBES AT, FORBES NT, HUIZINGA P, LAMBERTH SJ, MACKAY CF, PETERSEN C, TALJAARD S, WEERTS SP, WHITFIELD AK and WOOLDRIDGE TH (2013) Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data limited environment, *Estuarine, Coastal and Shelf Science* **130** 239-251.

VAN NIEKERK L, ADAMS JB, JAMES N, LAMBERTH S, MACKAY F, RAJKARAN A, TURPIE J, WEERTS S, and WHITFIELD AK (2020) An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. *African Journal of Aquatic Science* **45** (1-2) 199-216.

VAN NIEKERK L, ADAMS JB, LAMBERTH SJ, MACKAY CF, TALJAARD S, TURPIE JK, WEERTS SP and RAIMONDO DC (2019) (Eds). South African National Biodiversity Assessment 2018: Technical Report. Volume 3: Estuarine Realm. CSIR report number CSIR/SPLA/EM/EXP/2019/0062/A. South African National Biodiversity Institute, Pretoria. Report Number: SANBI/NAT/NBA2018/2019/Vol3/A. http://hdl.handle.net/20.500.12143/6373.

VAN NIEKERK L, NETO DS, BOYD AJ and HOLTZHAUSEN H (2008) *Baseline Surveying of Species and Biodiversity in Estuarine Habitats.* Report No. BEHP/BAC/03/04, Benguela Current Large Marine Ecosystem Programme, Swakopmund, Namibia.

VAN NIEKERK L, TALJAARD S, ADAMS JB, Lamberth SJ and WEERTS SP (2020) Experimental ecosystem accounts for South Africa’s estuaries: Extent, Condition and Ecosystem Services Accounts. Report produced by CSIR, South Africa. Report No CSIR/SPLA/SECO/IR/2020/0026/A.

VAN NIEKERK L, TALJAARD S, VAN DEVENTER H, ADAMS JB, LAMBERTH SJ, WEERTS SP and LEMLEY DA (2023) Southern African Estuaries: Provisional Estuarine Ecosystem Typing and Eco-social Indicators for Southern African Region. Report prepared as part of Africa's Living Rivers Programme: Knowledge Capture WRC project. CSIR Report. Stellenbosch, South Africa

VANDERPOORTEN A, KLEIN PJ (2000) Aquatic bryophyte assemblages along a gradient of regulation in the river Rhine. *Hydrobiologia* **410** 11-16.

VASQUEZ D, FLOWERS RW and SPRINGER M (2009) Life history of five small minnow mayflies (Ephemeroptera: Baetidae) in a small tropical stream on the Caribbean slope of Costa Rica. *Aquatic Insects* **31** (14) 319-332.

VAUGHT GL (1972) The life history and ecology of the stonefly Neoperla clyment (Newman) (Plecoptera: Perlidae). MSc thesis, North Texas State University.

VENTER N, COWIE BW, WITKOWSKI ET, SNOW GC and BYXRNE MJ (2017) The amphibious invader: Rooted water hyacinth's morphological and physiological strategy to survive stranding and drought events. *Aquatic botany* **143** 41-48.

VERCRUYSSE K, GRABOWSKI RC and RICKSON RJ (2017) Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation. *Earth-Science Reviews* **166** 38-52.

WALSH CJ and MITCHELL BD (1998) Factors associated with variations in the abundance of epifaunal caridean shrimps between and within estuarine seagrass meadows. *Marine and Freshwater Research* **49** 769-777.

WEBB JA, DOWNES BJ, LAKE PS and GLAISTER A (2006) Quantifying abrasion of stable substrata in streams: a new disturbance index for epilithic biota. *Hydrobiologia* **559** 443-453.

WELCOMME RL (1979) *Fisheries ecology of floodplain rivers*. Longman, London and New York, USA. 317 pp.

WELCOMME RL (1985) *River fisheries* (No. 262). FAO.

WELCOMME RL, WINEMILLER KO and COWX IG (2006) Fish environmental guilds as a tool for assessment of ecological condition of rivers. *River Research and Applications* **22** (3) 377-396.

WENTWORTH CK (1926) Methods of mechanical analysis of sediments (Vol. 11, No. 11). University of Iowa.

WEYL OLF and HECHT T (1998) The biology of *Tilapia rendalli* and *Oreochromis mossambicus* (Pisces: Cichlidae) in a subtropical lake in Mozambique. *South African Journal of Zoology* **33** (3) 178-188.

WHITE DS (2009) Coleoptera (Beetles) in Aquatic Ecosystems, *Encyclopedia of Inland Waters*, Elsevier 144-156 pp.

WHITFIELD AK (1994a). An estuary-association classification for the fishes of Southern Africa, *South African Journal of Science* **90** (7) 411-417.

WHITFIELD AK (1994b) Abundance of larval and 0+ juvenile marine fishes in the lower reaches of three Southern African estuaries with differing freshwater inputs. *Marine Ecology Progress Series* **105** 257-267.

WHITFIELD AK (2019) Fishes of Southern African estuaries: From species to systems. Smithiana Monograph No. 4. 495 pp.

WIKIPEDIA (2023a) *Lagarosiphon major,* https://en.wikipedia.org/wiki/Lagarosiphon_major, downloaded 27 April 2023.

WIKIPEDIA (2023b) Cynodon dactylon. <https://en.wikipedia.org/wiki/Cynodon_dactylon>. Downloaded on 27 April 2023.

WIKIPEDIA (2023c) *Pontederia crassipes*. https://en.wikipedia.org/wiki/Pontederia_crassipes, downloaded 26 April 2023.

WILDE EW and TILLY LJ (1981) Structural characteristics of algal communities in thermally altered artificial streams. *Hydrobiologia* **76** 57-63.

WILLOUGHBY NG and TWEDDLE D (1978) The ecology of the catfish *Clarias gariepinus* and *Clarias ngamensis* in the Shire Valley, Malawi. *Journal of Zoology* **186** (4) 507-534.

WINEMILLER KO and JEPSEN DB (1998) Effects of seasonality and fish movement on tropical river food webs. *Journal of fish Biology* **53** 267-296.

WINEMILLER KO and KELSO-WINEMILLER LC (2003) Food habits of tilapiine cichlids of the Upper Zambezi River and floodplain during the descending phase of the hydrologic cycle. *Journal of fish Biology* **63** (1) 120-128.

YAM RS and DUDGEON D (2005) Stable isotope investigation of food use by Caridina spp. (Decapoda: Atyidae) in Hong Kong streams. *Journal of the North American Benthological Society* **24** (1) 68-81.

YANG GY, TANG T, DUGEON D (2009) Spatial and seasonal variations in bethic algal assemblages in streams in monsoonal Hong Kong. *Hydrobiologia* **632** 189-200.

ZARFL C, LUMSDON AE, BERLEKAMP J, TYDECKS L AND TOCKNER K (2015) A global boom in hydropower dam construction. *Aquatic Sciences* **77** (1) 161-170. http://globaldamwatch.org/data/#core_global. (Accessed 8th November 2021).

ZEUG SC and WINEMILLER KO (2008) Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. *River Research and Applications* **24** (1) 90-102.

APPENDIX A. TYPOLOGY OF MAJOR SADC RIVERS AND ESTUARIES

The EFlows requirements of rivers are directly related to their hydrological flow regimes and geomorphic location in the landscape. These attributes are often associated with river ecosystem types, and various classification systems across the world have incorporated flow regime categories and longitudinal geomorphic zone classes in their hierarchies.

This appendix presents a summary of the work done for *Task 3 Complete a typology of major SADC rivers and estuaries*.

A.1. Selection of a hydrological representative study area for the SADC

The SADC is made up of 16 mainland and island member states, all of which have territory south of five degrees latitude. The SADC country polygons were extracted from the country boundaries of the world (Belgiu 2015). The team then workshopped the best representative level of catchment boundaries mapped in the BasinATLAS (Linke *et al.* 2019) in representing the hydrological boundaries that would predominantly overlap the SADC. The Strahler orders 5-9 of the HydroRIVERS were considered in the selection of basins, to ensure that the full reach of rivers from source to sea would be included in the study area. In agreement, the Level 4 HydroBasin polygons with a large degree of overlap with the country boundaries of these river orders were extracted and dissolved in ArcGIS 10.6 (ESRI 1999-2017) resulting in a total areal extent of 10 550 424 km^2 (Figure A.1).

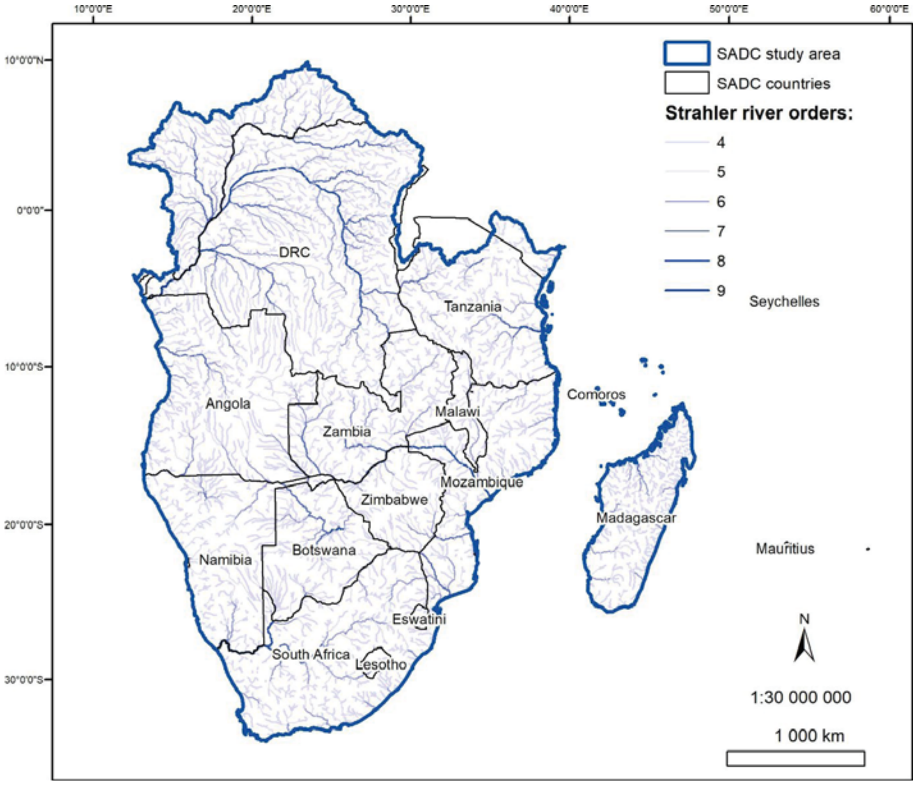


Figure A.1 The SADC study area with river extents from RiverATLAS (Linke *et al.* 2019) (orders 4 and above are displayed).

A.2. Inventory of spatial data sets available for typing SADC river and estuarine ecosystem types

The use of spatial datasets has enhanced the automation and typing of all ecosystem types across the globe. Literature and spatial data surveys were undertaken to list available and relevant spatial data sets for typing SADC river and estuaries. More than 25 global datasets were collected (Table A.1), and broad categories of types of datasets were identified:

1. **Orientation datasets** of the SADC countries and cities. Two datasets were identified, namely the country boundaries of the world, and cities.
2. **Broad climatic regions** were identified, including the Köppen-Geiger dataset (Beck *et al.* 2018), and the Freshwater Ecoregions of the World (FEOW) and FEOW Major Habitat Types (MHT) by Abell *et al.* (2008; 2011).
3. **Coastal Biogeography** was derived from Potts *et al.* (2015) which describes the major coastal regions of SADC.
4. **Hydrological boundaries or basins** is one of the layers of the latest version of the HydroATLAS, version 1 (Linke *et al.* 2019), offers 12 basin layers ranging from the continental scales at level 1, to the finest catchment boundaries at level 12 (As described in the previous chapter).
5. **River datasets.** Three river datasets are available at a global level: 1) The Global free-flowing rivers (Grill *et al.* 2019); 2) The RiverATLAS version 1 also from the HydroATLAS version 1 dataset (Linke *et al.* 2019); and 3) The GloRiC dataset (Dallaire *et al.* 2019).
6. **Estuarine datasets**: include the Global Estuary Database, global map of Intermittently Closed/Open Lakes and Lagoons (ICOLLs) (McSweeney 2017), Global Distribution of Seagrasses, Global Distribution of Saltmarsh, World Atlas of Mangroves (2010); Global Distribution of Mangroves USGS (2011) and the Global Distribution of Modelled Mangrove Biomass (2014).
7. **Digital elevation and surface models** included six datasets generated at a global scale, from a number of sensors, namely the Advanced Land Observation Satellite (ALOS) Digital Surface Model (DSM) and DEM (Takaku *et al.* 2014; 2020), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM (Abrams *et al.* 2020) and the two Shuttle Radar Topography Mapper (SRTM) DSMs at 30- and 90-m spatial resolution (Jarvis *et al.* 2008). However, preliminary investigations indicate that the vertical accuracy is lacking to assist in delineating the extent of tidal variation and flood plain inundation.
8. **Artificial and natural wetlands** included nine datasets for artificial instream wetlands.
9. **South African datasets** that can be used for comparison of global datasets included two layers, the South African artificial wetlands, and river ecosystem types (Nel *et al.* 2011a&b; Van Deventer *et al.* 2019; Van Deventer *et al.* 2020) and the South African National Estuary Ecosystem Classification (Van Niekerk *et al.* 2019; 2020).

Table A.1 Inventory of spatial datasets relevant to river and estuarine ecosystem typing for the SADC.

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
Global: Orientation datasets: political boundaries and reference points					
World cities	Location of large cities and their population	ESRI (2013)	Points (1:1 000 000)	Location of large cities from United Nations and United States Census	Smaller cities are not included
World countries	Country boundaries of the world.	Belgiu (2015)	Polygon (1:1 000 000)	Unknown.	South Africa/Namibian border in dispute at Orange Estuary northern bank.
Global: Climatic regions					
Climatic regions	Köppen-Geiger climate classification maps at 1 km resolution	Beck *et al.* (2018)	Raster dataset (converted to polygon (1:1 000 000)	Modelling of the world's climatic regions as raster dataset. Five main classes – tropical, dry, temperate, continental and polar climatic regions	Global-scale data.
Freshwater ecoregions of the world (FEOW) and Major Habitat Types (MHT)	Provides a global biogeographic regionalization of the Earth's freshwater biodiversity	Abell *et al.* (2008; 2011)	Polygon (shapefile and KML) (±1:1 000 000)	Large areas representing distinct assemblages of freshwater communities and species	Add description here
Coastal Biogeographical Regions					
Biogeographical regions	Southern Africa biogeographical regions	Potts *et al.* (2015)	Lines (1:1 000 000)	Generated from Potts et al 2017. by N James based on coastal features	Generated at a regional scale. Transition zones not included
Global: Digital Elevation Models (DEMs)					
ALOS DSM Version 3.2	DSM includes elevation of surface features such as buildings	Takaku *et al.* (2014; 2020)	GeoTIFF raster with 30-m spatial resolution in 1°x1° tiles	Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM)	Elevation data low resolution
ALOS PALSAR	RTC DEM with focus on the Americas	Takaku *et al.* (2014; 2020)	GeoTIFF raster with 12.5 m spatial resolution	Phased Array type L-band Synthetic Aperture Radar (PALSAR)	Elevation data low resolution
ASTER version 3	DEM between 83°N and 83°S	Abrams *et al.* (2020)	GeoTIFF raster with 30-m resolution in 1°x1° tiles	Spaceborne Thermal Emission and Reflection Radiometer	Elevation data low resolution

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
HydroSHEDs version 1	A number of raster datasets include hydrologically conditioned elevation, drainage directions, flow accumulation, river network and drainage basins were derived from the void-filled SRTM 90 m DSM	Lehner *et al.* (2008)	Various raster, with the upscaled SRTM DEMs to three resolutions (±90 m, 500 m, 1 km and 10 km at the equator).	GIS has been used to derive the flow accumulation and basins from the 90-m spatial resolution SRTM DSM	Elevation data low resolution
SRTM 30- and 90-m spatial resolution DEMs	DEMs between 60°N and 60°S	Jarvis *et al.* (2008)	ASCII and GeoTiff raster format at various scales	Spaceborne Imaging Radar data improved by flattening, void filling and interpolation to get Version 4 (Reuter *et al.* 2007)	Reported vertical error < 16 m. Small holes in data can be an issue in hydrological modelling
Global: Catchment boundaries					
HydroBASINS version 1	Watershed boundaries and sub-basin delineations at a global scale (with and without lakes)	Linke *et al.* (2019)	Polygon (±1:1 000 000)	Uses HydroSHEDS database at 15 arc-second (~500 m) spatial resolution	See HydroSHEDS.
Global Estuarine datasets					
Global Estuary Database	This dataset shows the global distribution of over 1,300 estuaries, including some lagoon systems and fjords	Alder (2003)	The majority of estuaries are represented by polygons, except for 44 records for which points are available. Resolution highly variable across datasets	Water bodies were selected so as to include the estuaries of all major rivers, as well as the small estuaries of countries without major rivers. No specific minimum size/discharge was applied. The information was gathered from a large number of sources (reports, journals, electronic resources. Dataset contains information about the name, location, surface area and mean freshwater input	Very low accuracy, only a very small number of estuaries identified in SADC (<50)
Global Distribution of Mangroves USGS (2011)	Dataset shows the global distribution of mangrove forests, derived from earth observation satellite imagery	Giri *et al.* (2011)	Polygon dataset given with a 30 m resolution	The dataset was created using Global Land Survey (GLS) data and the Landsat archive ~ 1,000 Landsat scenes were interpreted using hybrid supervised and unsupervised digital image classification techniques	Small patches (< 900-2,700 m^{-2}) of mangrove forests cannot be identified using this approach
Global Distribution of Modelled Mangrove Biomass (2014)	Dataset shows the modelled global patterns of above-ground biomass of mangrove forests	The Nature Conservancy	Distributed alongside the vector dataset is a global (30 arc-sec) raster version	The work is based on a review of 95 field studies on carbon storage and fluxes in mangroves world-wide. A climate-based	The model used to generate this dataset predicts potential biomass rather than actual

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
		Hutchison *et al.* (2014)	showing predicted mangrove above-ground biomass in tonnes/hectare. (Resolution is variable)	model for potential mangrove above-ground biomass was developed, with almost four times the explanatory power of the only previous published model. The map shows the high variability in mangrove above-ground biomass and indicates areas that could be prioritised for mangrove conservation and restoration	biomass. Where mangroves have been degraded, the model will not account for this
Global Distribution of Saltmarsh	This dataset displays the distribution of saltmarshes globally	UNEP-WCMC (2016); Mcowen *et al.* (2017)	The dataset consists of one polygon layer, one point layer, and an accompanying Access database that contains species information (linked exclusively to the point dataset). Resolution between 1:10,000 to 1:4,000,000 (largely 1:10,000-1:100,000)	The dataset is drawn from occurrence data (surveyed and/or remotely sensed). The dataset was developed to provide a baseline inventory of the extent of the global distribution of saltmarshes	Low resolution, significant areas of saltmarshes missing from dataset
Global Distribution of Seagrasses	Shows the global distribution of seagrasses	NEP-WCMC and Short (2021)	1:1 000 000	This dataset is composed of two subsets of point and polygon occurrence data. This dataset was created from multiple sources (in 128 countries and territories), including maps (of varying scales), expert interpolation and point-based samples. Before inclusion in the dataset, occurrence records were reviewed using published reports, peer-reviewed literature and expert consultation	Relatively low accuracy given the scale of the data
Intermittently Closed/Open Lakes and Lagoons (ICOLLs)	Their global distribution and boundary conditions.	McSweeney *et al.* (2017)	Point data	The global distribution of ICOLLs was mapped through online virtual globes, namely Google Earth and supplemented	A significant number of smaller estuaries was missed with the authors mainly concentrating on South Africa

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
				with literature mining of entrance condition	
World Atlas of Mangroves (2010)	This dataset shows the global distribution of mangroves	Spalding *et al.* (1997; 2010)	Data consist of polygon layers (1:1 000 000)	The dataset was created mostly from satellite imagery processed at UNEP-WCMC or FAO. For a number of countries, existing (WCMC-012, 1997) or newly available (vector) data were incorporated. Experts with detailed field knowledge were consulted for validating the maps	In some areas, there is an offset and/or mismatch in the position of the mangrove layer in relation to the coastline: this is probably caused by a number of factors, including varying data sources, differing scales to which the image interpretation was conducted, differing sensor types, differing optical bands, etc.
Global: Rivers					
HydroRiVERS version 1	River line network derived from a DEM that have a catchment area of at least 10 km^2 or an average river flow of 0.1 cubic meters per second, or both. Attribute fields have integrated ±56 hydro-environmental variables	Linke *et al.* (2019)	Line (±1:1 000 000)	Uses HydroSHEDS (SRTM) at 15 arc-second (~500 m) spatial resolution for river lines. WaterGAP model for discharge checked against 3 003 gauging stations from the Global Runoff Data Center	Uncertainties in discharge were observed in certain regions, in particular arid and semi-arid areas
Global free-flowing rivers dataset	Connectivity status of rivers of the world, calculated for the same extent as the Lehner and Grill (2013) data	Grill *et al.* (2019)	Line (±1:1 000 000)	Connectivity status calculated from fragmentation, flow regulation, sediment blockage, water consumption, road density, and urban extent indicators. Data generated using HydroSHEDS river lines; global remote sensing data (nightlight intensity, erosion); and global hydrological, water resource, sedimentation models	Not accurate in many regions due to global scale of data, modelling and calibration

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
GloRiC	A hydrologic, physio-climatic, and geomorphic sub-classification, as well as a combined type for every river reach, resulting in a total of 127 river reach types	Dallaire *et al.* (2019)	Line (±1:1 000 000)	Uses classification categories on HydroATLAS data. See technical documentation for more details	Global classification criteria may have inaccuracies for certain local basins
Global: Artificial and natural wetlands					
ASTER Water Body Dataset (ASTWBD)	Identifies all water bodies as river, lake or ocean. Each water body tile corresponds to ASTER (space-borne radar satellite) DEM tile.	Abrams *et al.* (2020)	GeoTIFF format (raster) with 30-meter spatial resolution and 1°x1° tiles (1:500 000)	Processed from ASTER GDEM data at ±30-m spatial resolution	Level 1A scenes between 1 March 2000 and 30 November 2013 were used to create the layer and classified to three categories: ocean, river or lake
Dam and Reservoir Atlas of Southern Africa (DRASA)	Spatial location and fact sheet on 600 dams in Angola, Botswana, Namibia, South Africa and Zambia.	(SASSCAL, In prep)	To be published still.	SASSCAL aims to make all resources in DRASA freely available via the SASSCAL Data and Information Portal (http://data.sasscal.org/)	SASSCAL works with national authorities and dam operators and has summarized data gathered from this engagement
Future Hydropower Reservoirs and Dams (FHReD) database	Database of 3 700 proposed dams.	Zarfl *et al.* (2015)	Point (1:1 000 000)	Compilation of existing databases, literature, grey literature, internet searches	Not aligned to river network as GOODD and GRanD. Some errors as proposed developments so locations are not certain
Global Georeferenced Database of Dams (GOODD)	Database of 38 667 dams.	Mulligan *et al.* (2020)	Point (1:2 000)	Heads up digitizing from Google Earth by community	Digitized between 2007-2011 with additional updates in 2016. A reservoir length of 500 m and dam wall length of 150 m for small dams could be identified with certainty from the low-resolution imagery
Global lakes and wetlands database	Compilation of large lakes and reservoirs, smaller water bodies.	Lehner and Döll (2004)	Polygon, and global raster (1:100 000)	Compilation of existing databases	Seven datasets that were published between 1995 and 2000 were combined. Data is

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
					limited to water bodies larger than 0.1 km²
Global Reservoir and Dam database (GRanD)	Database of 7 320 dams and associated reservoirs.	Lehner *et al.* (2011)	Point (dam) and polygon (reservoir) (1:100 000)	Compiled from existing databases. Version 1.3 contains dams and reservoirs until 2016	Provides a high-resolution and extensively validated global dataset of reservoir polygons and their associated dams. Data was collected from 11 institutions and is curated by McGill University
Global Surface Water (GWS) explorer and related products	Changes in the extent of open waterbodies mapped from Landsat series of sensors between 1984 and about 2016, followed by Sentinel-2 at a 30-m spatial resolution.	Pekel *et al.* (2016)	Raster datasets at 30-m spatial resolution (1:1 000 000)	Extracted from the Landsat (1984-2016) and Sentinel2 (2016 to date) satellite images at a 30-m spatial resolution	Testing showed that the classifier produced less than 1% of false water detections, and missed less than 5% of water. Each pixel was classified for each year as open water, land or non-valid, with further classifications based on temporal trends
HydroLAKES version 1	Shoreline polygons of all global lakes with a surface area of at least 10 ha (1.4 million lakes) Shore length, average depth, volume and residence time.	Messager *et al.* (2016)	Polygon (lake), point (pour points) scales ranging between 1:250 000 and 1:1 000 000.	Compilation of existing datasets	Includes SRTWM water body Data, GRanD, GLWD and region-specific data sets such as United States and Canadian hydrographic data. Each has varying underlying accuracy
SRTM Water Body dataset	Identifies ocean, lake and river shorelines. I cannot access this from https://earthexplorer.usgs.gov/???	USGS (2020)	Polygons extracted from 30 m SRTM (1: 1000 000)	Shorelines processed from 30 m SRTM supported by Landsat land cover	Appropriate for SADC extent and scale mapping of ecosystem types, but do not detect and report on shallow wetlands, palustrine wetlands, or those smaller than 90 m² and narrow in shape

Name	Data description	Citation of the data	Data format and scale (assumed approximated scale if not provided in metadata or reports)	Methods used in generating the dataset	Accuracy / Confidence
Republic of South Africa datasets: comparisons					
South African Estuaries Classification	Dataset provides information on the location and type of all outlets along the south African Coast.	Van Niekerk *et al.* 2020	Point data (1:2000 000)	Historical data on estuary types were collated and estuary type assigned in a workshop environment and visually confirmed on Google Earth	Smaller estuaries and micro-estuary types overlapped and needs ground truthing to assign class
NMU Blue Carbon Ecosystem	Polygons mapping Blue Carbon Habitats types in the South African EFZs.	Raw *et al.* (in press)	Polygons (1:2 000)	Heads-up digitising of all estuarine Blue Carbon habitats (mangroves, sea grass, salt marsh) by multi-annual images from Google Earth Pro	High confidence.
NMU National botanical database	Polygons mapping main habitat types in the South African EFZs for larger estuaries (122)	Adams *et al.* (2016; 2019)	Polygons (1:2 000)	Heads-up digitising of estuarine habitats (mangroves, sea grass, salt marsh, open water and sand/mud) by multi-annual images from Google Earth Pro	Not assessed
SAIIAE artificial wetlands	Artificial wetlands of South Africa as a data layer.	Van Deventer *et al.* (2019)	Polygon data (geodatabase and shp format) at 1:50 000 scale.	Various datasets have been integrated, refined and additional dams mapped, while the dams register coordinates was also used to validate polygon dam locations.	Accuracy was not assessed.
SAIIAE NWM5	Including the extent of the EFZ and names of the estuaries.	Van Deventer *et al.* (2020)	Polygons (1:2 000-1:10 000 around the estuarine habitats)	Habitat mapping through heads-up digitising informed by a variety of datasets	Not assessed.
SAIIAE river lines	The river ecosystem types of South Africa were typed according to ecoregions, flow regime (perennial/seasonal or non-perennial) and longitudinal geomorphic zones.	Smith-Adao *et al.* (2018)	Line in geodatabase and shp file format at ±1:500 000 for mainstem rivers and some tributaries to 1:250 000)	Calculated based on input from aggregated ecoregions, two flow types (perennial and non-perennial) and four longitudinal geomorphic zones	Accuracy was not assessed.

A.3. Typology for major SADC rivers

This section provides an overview of relevant classification systems for river ecosystem types; and spatial datasets available for SADC were reviewed in this context. Subsequently, a typing methodology for rivers at the SADC scale is proposed.

A.3.1. Classification systems of river ecosystem types

The IUCN has recently published a new typology for ecosystems (Keith *et al.* 2020). Rivers and streams are considered one of the biomes (type F1) under the wetlands realm (Table A.2), and '… includes lotic ecosystems throughout the world, flowing from elevated uplands to deltas, estuaries, and lakes. They are defined primarily by their linear structure, size, and flow regimes … .' (Keith *et al.* 2020: 105). At the third tiered level of the hierarchical classification system, six ecosystem functional groups (EFGs) are presented based on flow regimes and geomorphic position of the longitudinal section of rivers in the landscape. Four flow regimes are considered: permanent, seasonal, episodic, and freeze-thaw rivers and streams (Table A.2). For the longitudinal geomorphic zones, two categories are considered, including upland, and lowland rivers under the permanent and seasonal flow categories.

Table A.2 Ecosystem functional groups related to the Rivers and streams biome of the freshwater realm, as defined in the ecosystem typology of the IUCN (Keith *et al.* 2020).

Realm	Biome	Ecosystem Functional Group
Freshwater	F1 Rivers and streams	F 1.1 Permanent upland streams
Freshwater	F1 Rivers and streams	F 1.2 Permanent lowland rivers
Freshwater	F1 Rivers and streams	F 1.3 Freeze-thaw rivers and streams
Freshwater	F1 Rivers and streams	F 1.4 Seasonal upland streams
Freshwater	F1 Rivers and streams	F 1.5 Seasonal lowland rivers
Freshwater	F1 Rivers and streams	F 1.6 Episodic rivers

The IUCN EFGs present a refinement of the earlier river types listed by the Ramsar classification system (Scott and Jones 1995), where two types of rivers and streams were listed under Inland wetlands, namely 'Permanent rivers and streams; includes waterfalls' and 'Seasonal and irregular rivers and streams'.

The South African classification system for rivers offers further refinement of both global typologies discussed above (Ollis *et al.* 2013; 2015). The authors provide an overview of classification systems of wetlands globally and in South Africa and proposed the use of nine longitudinal geomorphic zone categories for rivers at level 4B of the tiered South African hierarchical system, based on earlier work of river specialists (Rowntree and Wadeson 1999; Rowntree *et al.* 2000). The implementation of the classification framework of South African rivers, was first done by Nel *et al.* (2011a&b) for the first

South African freshwater conservation project, the National Freshwater Ecosystem Priority Areas (NFEPA). For NFEPA, river ecosystem types were distinguished at (a) regional levels that represent broad climatic and geological diversity; (b) flow regimes (perennial and non-perennial); and (c) longitudinal geomorphic zones. Perennial (i.e. permanently flowing rivers) includes seasonal rivers while non-perennial (i.e. not permanently flowing rivers) includes ephemeral rivers. River reaches were assigned three attribute fields of coding based on 31 aggregated Level 1 ecoregions (Kleynhans *et al.* 2005), to represent the broad regional diversity. Flow regimes were interpreted from surface water visible in the river channel on historically, sporadically-available aerial photographs, used to compile the topographical map series of the country (DLA: CDSM, 2006). Today, continuous imagery are available at space-borne level to improve and refine flow regime categories, however, information from weirs are critical to supplement flow regime typing also using sub-surface flow information (Smith-Adao *et al.* 2018; Van Deventer *et al.* 2019). Four aggregated longitudinal geomorphic zone classes (mountain stream, upper foothill, lower foothill, and lowland rivers) from the original nine, defined according to channel slope categories of Rowntree *et al.* (2000), were automated in Geographic Information Systems (GIS) by Moolman (2008) to subdivide the river lines dataset (Smith-Adao *et al.* 2018). The update of the river ecosystem types for the National Biodiversity Assessment of 2018 (NBA 2018) resulted in a total of 222 river ecosystem types (Van Deventer *et al.* 2019).

The use of readily available geospatial datasets with improved spatial accuracies has enhanced the automation and typing of all ecosystem types across the globe. The aim of this part of the project was to assess the possibility of applying a river ecosystem typology to SADC rivers; comparable to what was used in the South African rivers in the NFEPA, NBA 2011 and NBA 2018 projects. The next sections review the spatial datasets that are available for typing river ecosystem types of SADC spatially in a GIS.

A.3.1.1 Global River Classification (GloRiC)

Dallaire *et al.* (2019) selected seven variables through a principal component analysis from the RiverATLAS version 1 dataset to generate the Global River Classification (GloRiC) of river ecosystem types at a global scale. The types are defined using two hydrologic variables (long term average discharge and flow variability), three physio-climatic variables (long term average of the minimum air temperature of the coldest month, climate moisture, and elevation), and two geomorphic variables (stream power, and lake-wetland influence). Based on the number of classes selected for each variable a total of 1 039 classes out of the 1 440 theoretically possible classes were observed at a global scale. The authors then reduced the 1 039 classes to generate 127 global river ecosystem types by removing indicators such as flow variability and combining other variables. Through a K-means clustering the 127 global river ecosystem types were further reduced to 30 to reduce the number of types and minimise duplication of types which show a high degree of similarity. Of these 30 types, five appear dominant across SADC (Figure A.2). This dataset therefore presents the first global assessment of river ecosystem types.

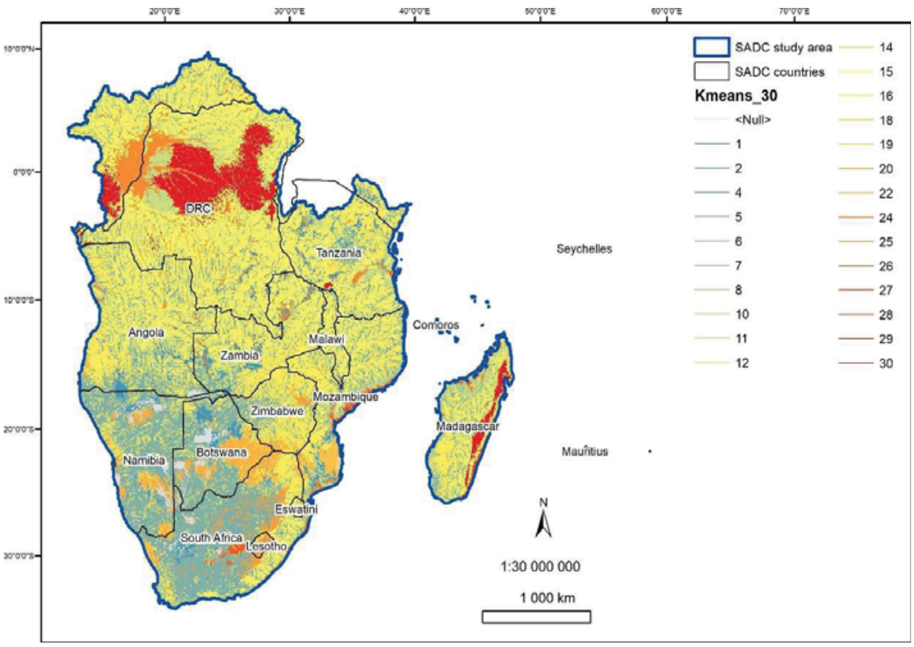


Figure A.2 **River reach groups (30) mapped in the Global River Classification (GloRiC) dataset (Dallaire *et al.* 2019) for the Southern African Development Community (SADC) study area.**

There are some key shortcomings in using the GloRiC river ecosystem types for EFlows purposes for this project, and in SADC:

- Manageability of the classifications at a global scale has led to a trade-off for representativeness. Multiple levels of clustering and aggradation that considered the global range of variables were used to accomplish this.
- The use of stream power (product of the maximum long-term average monthly discharge and the average stream gradient) instead of stream gradient meant there was a lack of traditional, longitudinal geomorphic zone classes representing channel morphology that are often linked to stream gradient.
- There was no consideration of aquatic ecology in the final classification even though this was included in the GloRiC theoretical framework.
- There was no formally recognised ecosystem typology, especially for the K-means clustered classes.

A.3.1.2 Existing climate, bioregions and ecology river ecosystem types

Three datasets that represent classes of climatic and ecological regions (Table A.1) across the globe were available for SADC:

- FEOW (Abell et al. 2008): The FEOW were modelled to represent a large area encompassing one or more freshwater systems with a distinct assemblage of natural freshwater communities and species (Abell et al. 2008; 2011) and 426 ecoregions were identified globally. Fifty-four

FEOW ecoregions overlap with SADC (Figure A.3), of which 47 are on the mainland, five are found in Madagascar, and two are related to the island groups.

- FEOW MHT: The 426 geographically distinct FEOW were grouped into 12 global MHTs based on similarity in biological, chemical, and physical characteristics and are roughly equivalent to biomes for terrestrial systems. Eight of the 12 MHTs occur in SADC for the mainland and Madagascar (Figure A.4), while another MHT, the Oceanic islands, applies to the smaller islands.
- The Köppen-Geiger climate classification: This system was constructed using an ensemble of high-resolution, topographically corrected climatic maps of climate conditions between 1980 and 2016 (Beck *et al.* 2018). It divides the world into five main climate groups based on temperature and precipitation patterns (tropical, dry, temperate, continental, and polar). At a second classification level the seasonality of precipitation (e.g. rainforest, monsoon, savannah) is defined, while at the third level divisions are based on temperature ranges. The present-day climate conditions in SADC (Figure A.5) were collected from the Köppen-Geiger climate classification map produced at a 1-km spatial resolution. The northern and north-eastern part of the study area are mainly classed as tropical, whereas the southern sections are mostly arid. Temperate climates predominate in the middle of SADC.

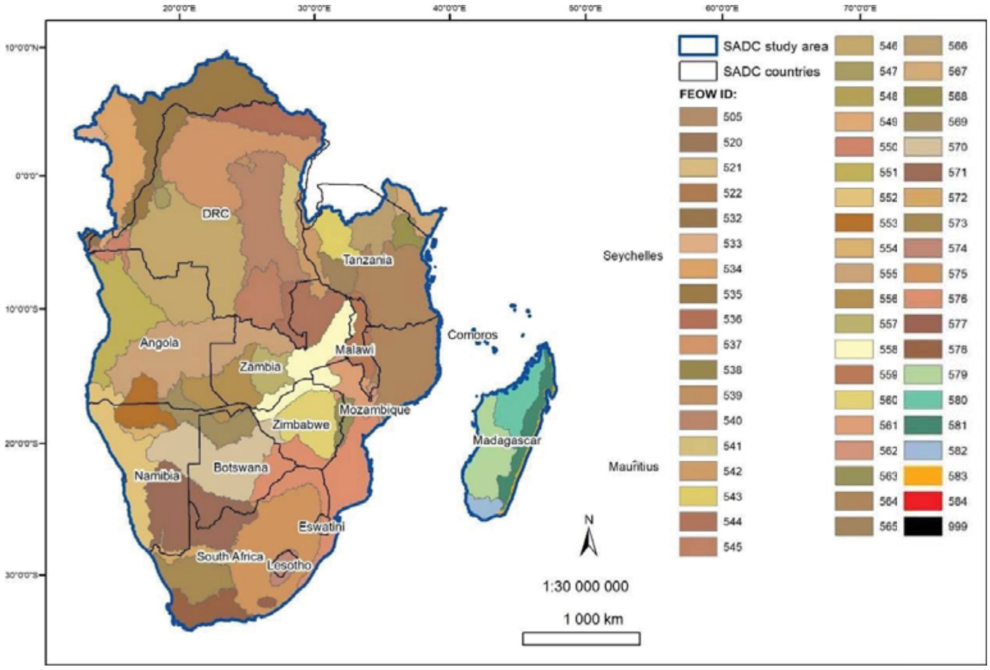


Figure A.3 **Freshwater Ecoregions of the World (Abell *et al.* 2008) for the Southern African Development Community (SADC) study area.**

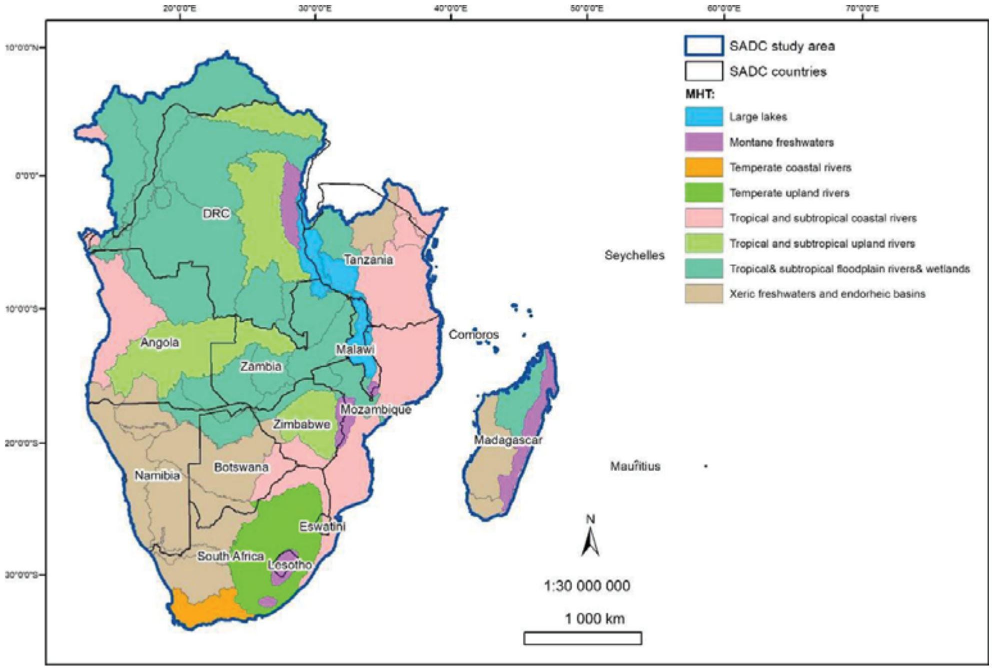


Figure A.4 Freshwater MHTs (Abell *et al.* 2008; 2011) displayed with the boundaries of the FEOW for the SADC study area. The ninth MHT that is associated with SADC (Oceanic Islands) is not shown.

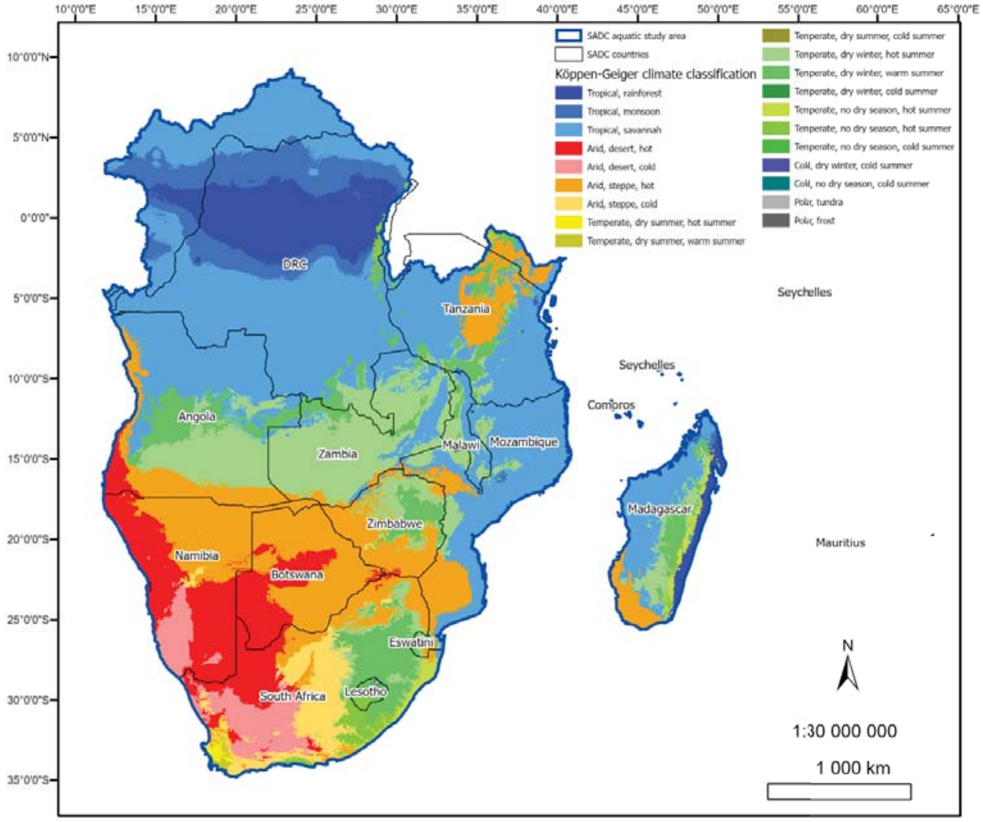


Figure A.5 The Köppen-Geiger climate (1-km spatial resolution; reference) classification for the extent of the SADC study area.

A.3.1.3 Flow regimes for typing river ecosystems

To date, no single of the river datasets indicated flow categories, either aligning with the two IUCN global ecosystem type categories of permanent or seasonal and intermittent types, or the South African categories of permanent, seasonal or ephemeral. One alternative option, is the stream power attribute in the GloRiC database, presenting a continuous variable ranging from 0 to 43.5, as illustrated in Figure A.6.

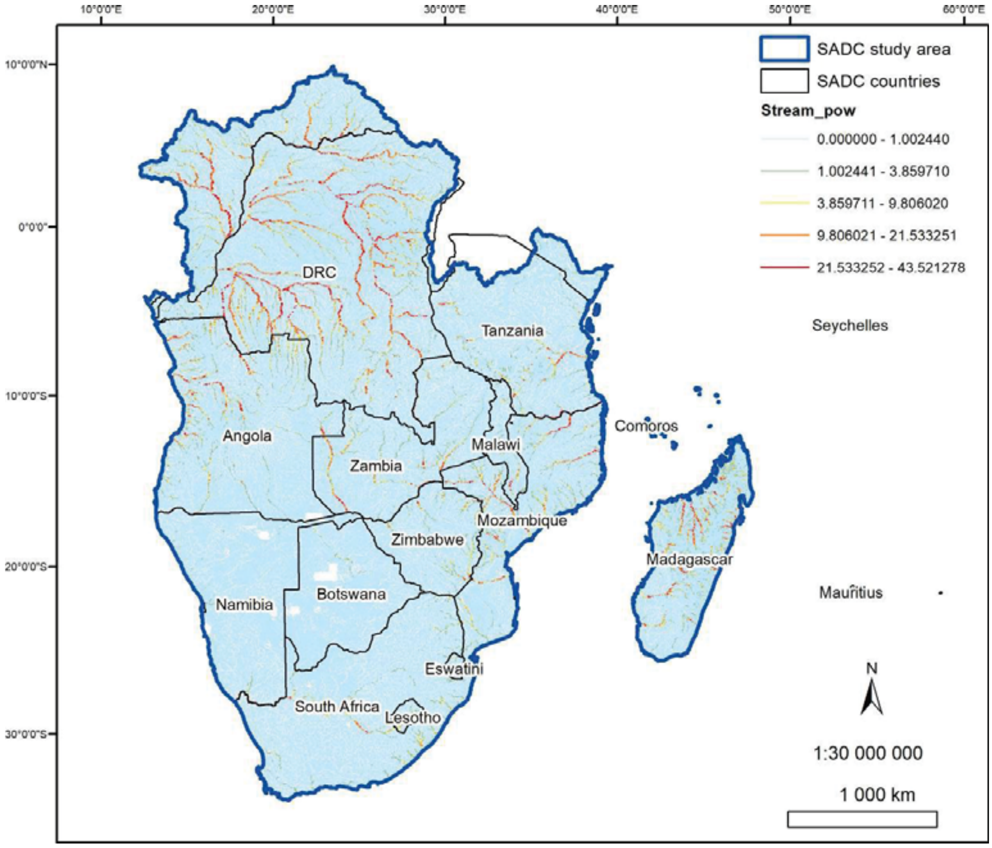


Figure A.6 Stream power from the GloRiC dataset (Dellaire *et al.* 2019), mapped according to Jenks natural breaks.

A.3.1.4 Longitudinal geomorphic zones

Nine longitudinal geomorphic zone classes, excluding the source zone of a river that is challenging to represent on maps, were proposed by Rowntree *et al.* (2000) based on various gradient thresholds extracted between each contour gradient from 1: 50 000 topographic maps, and other criteria (Table A.3). Six of these classes are defined based on threshold of gradient, with an additional three rejuvenated classes in cases where higher gradient classes occur downstream between the reaches of lower gradient classes (Table A.3). The boundaries of river reaches are marked by sharp breaks in channel gradient and suggest that a 50% or greater change is "*almost certainly significant"* and a less than 20% change is "*probably not significant*" (Rowntree *et al.* 2000:170). Lastly, they suggest that "*short reaches of steeper or gentler gradients may be included in a longer zone"* (Rowntree *et al.* 2000:170). The gap of significance between 20% to 50% and the use of vague terms such as *may be*, *probably*, and *almost certainly* indicates the reach determination was not entirely quantitative and rather guided by expert knowledge.

Table A.3 Differences between longitudinal geomorphological classification presented by Rowntree *et al.* (2000), Moolman (2008) and the categories used in the NBA 2011 and 2018

Gradient and slope classes			Classification		
Gradient	Percentage	Decimetre per km#	Rowntree *et al.* (2000)	Moolman (2008)	NBA 2011 and 2018
Zones associated with a normal profile					
>0.1	>10%	1000+	Mountain head water stream (A)	Headwater (A)	Mountain stream
0.04-0.01	4-10%	400 to 1000	Mountain stream (B)	Mountain stream (B)	Mountain stream
0.02-0.04	2-4%	200 to 400	Transitional (C)	Transitional (C)	Mountain stream
0.005-0.02	0.5-2%	50 to 200	Upper foothills (D)	Upper foothills (D)	Upper foothill
0.001-0.005	0.1-0.5%	10 to 50	Lower foothills (E)	Lower foothills (E)	Lower foothill
0.0001-0.001	0.01-0.1%	1 to 10	Lowland river (F)	Lowland river (F)	Lowland river
Additional Zones associated with a rejuvenated profile					
>0.02	>2%	200+	Rejuvenated bedrock fall / cascades (Ar, Br, Cr)	No rejuvenated classes, assessed as normal profile	No rejuvenated classes, assessed as normal profile
0.001-0.02	0.5-2%	50 to 200	Rejuvenated foothills (Dr, Er)		
<0.005	<0.5%	<50	Upland floodplain (Fr)		

$^{\#}$ From Linke *et al.* (2019).

For South Africa, Moolman (2008) automated the original gradient classes of Rowntree *et al.* (2000) to matching slope classes (Table A.3) and typed the national 1:500 000 rivers dataset of the country in GIS. Only the six classes based on slope thresholds were used and not the three rejuvenated classes. For the NBAs of 2011 and 2018 (Nel *et al.* 2011a&b; Van Deventer *et al.* 2019), these six classes were aggregated into four categories, being mountain streams, upper and lower foothills and lowland rivers for biodiversity typing and assessment of the South African river ecosystem types (Table A.3). Prior to discovering the slope classes in Linke *et al.* (2019), the team considered repeating the automation done by Moolman (2008) to SADC rivers. This meant that new tools in currently available GIS software, which can be used for calculating the longitudinal slope of river lines, were investigated as part of this study.

The river lines from the RiverATLAS version 1.0 (Linke *et al.* 2019), however, already contains calculated average stream gradients per reach in the unit of dm/km (Figure A.7). The gradient was derived from the 3 arc-seconds spatial resolution (~ 90-m spatial resolution at the equator) using the

EarthEnv-DEM90 DSM (Robinson *et al.* 2014). This DSM is a combination of the SRTM v4.1 and ASTER GDEM v.2 data products, where sinks making up single pixel were removed, and their value adjusted to the minimum elevation of their eight surrounding pixels. The 3 arc-second pixels were then aggregated to 15 arc-second spatial resolution (~450 m spatial resolution at the equator), using the 'minimum' statistic. This was to match the resolution of the raster from where the slope will be derived, to the resolution of the original DEM from which the river centerlines were derived; and to preserve the valley-bottom height within the larger pixel. Finally, the stream gradient was calculated as the ratio between the elevation drop within the river reach and the length of the reach (Linke *et al.* 2019). This precalculated stream gradient in field “sgr_dk_rav” can be used to derive the longitudinal geomorphic zone categories for the rivers (Figure A.7).

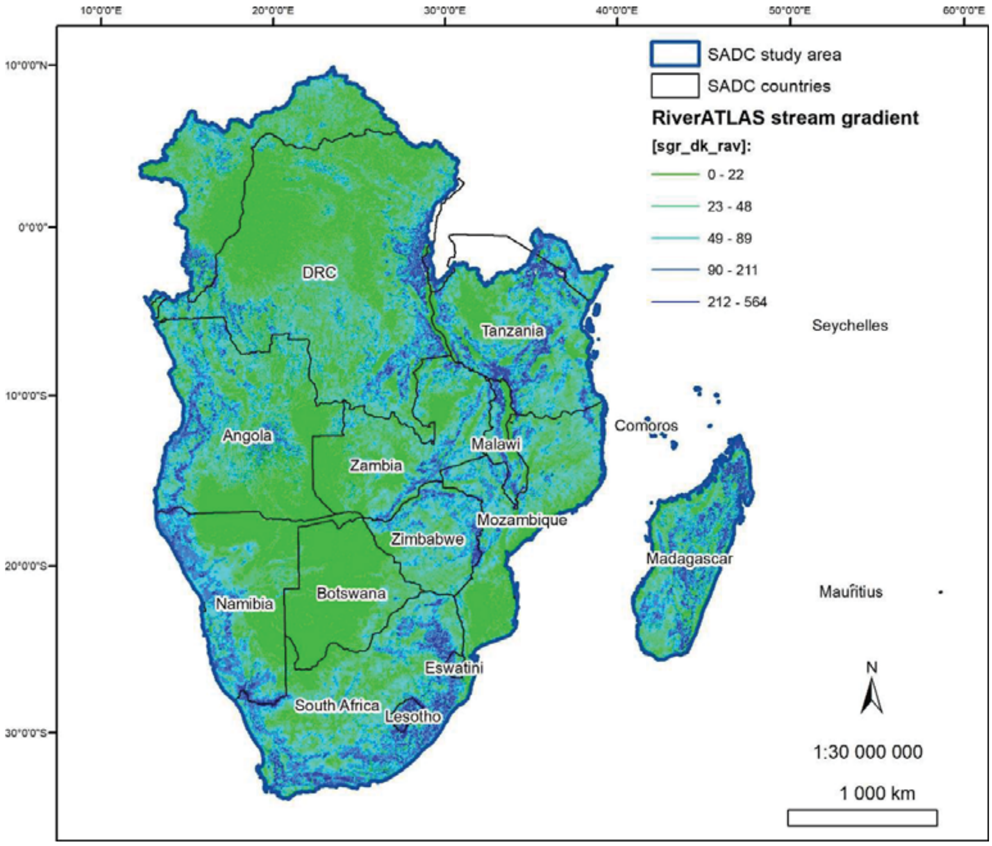


Figure A.7 Slope categories in the RiverATLAS version 1 (Linke *et al.* 2019).

The longitudinal geomorphic typing of South African rivers as classified by Moolman (2008) and used in the NBA of 2011 and 2018, was compared with the interim results of the typing derived from the RiverATLAS’ gradient field (Figure A.8).

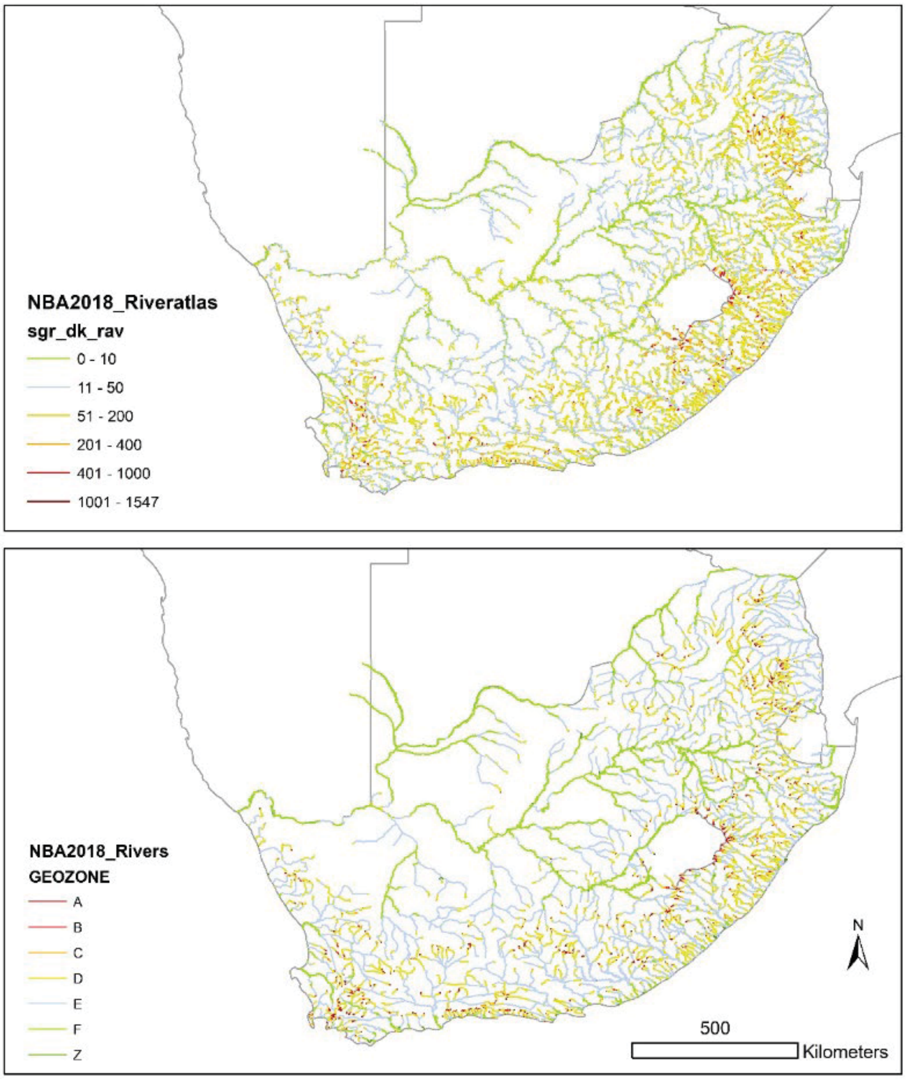


Figure A.8 **Longitudinal geomorphic zone classes derived from (A) Moolman (2008) and (B) derived from the RiverATLAS (Linke *et al.* 2019).**

A.4. Provisional Ecosystem Typing of Southern African Rivers

An inventory of available spatial data for SADC rivers was compiled of freely available/open source spatially-explicit datasets that can be used for the typing of river ecosystems (Table A.1). Most promising, the RiverATLAS v 1.0 (Linke *et al.* 2019) offers a consolidated collection of datasets that could be considered for representing the extent of the rivers of the study area, but also offering key attribute fields for the typing of river ecosystems. Also, in RiverATLAS, the FEOWs and FEOW MHTs offer regional-based information, comparable to the ecoregions used in South Africa for their river ecosystem types.

Initial work on typing suggested implementing a similar method to that used in the classification of South African Rivers for NBA (Nel *et al.* 2004), which included a typing based on ecoregions, flow regimes and longitudinal slope categories would be feasible. Subsequent to this, the team tested options for classification based on:

- The spatial datasets compiled as part of the work done in context of the South African Rivers for NBA (Nel *et al.* 2004).
- Review of an independent existing classification for the Zambezi Basin, which was done with the purpose of extrapolating DRIFT-based equations across that basin.
- Team discussions.

Three of the five attributes used for an existing classification for the Zambezi Basin are not available as shapefiles, i.e. they were determined through local knowledge or the evaluation of Google images, for example, for Rosgen's (1994) channel type, and there were concerns that this was too resource intensive for application at the SADC / study area scale. Thus, the aim of this exercise was to see if a similar classification could be achieved using the GIS datasets complied and, if so, which were the most appropriate for use in this project. This entailed selection of datasets for:

- River lines
- Climate, bioregions and ecology river ecosystem types
- Longitudinal geomorphic zones or Slope
- Distinguishing "tricky features" such as floodplains and gorges.

A.4.1.1 Selected spatial datasets

Datasets for river lines

Selection of river lines from the RiverATLAS dataset was suggested based on their Strahler River Order. Orders 4 and lower provide a resolution that is too fine to be used in the DRIFT framework at the basin scale (Figure A.9). Therefore, the river network for this project has been limited river orders ≥5.

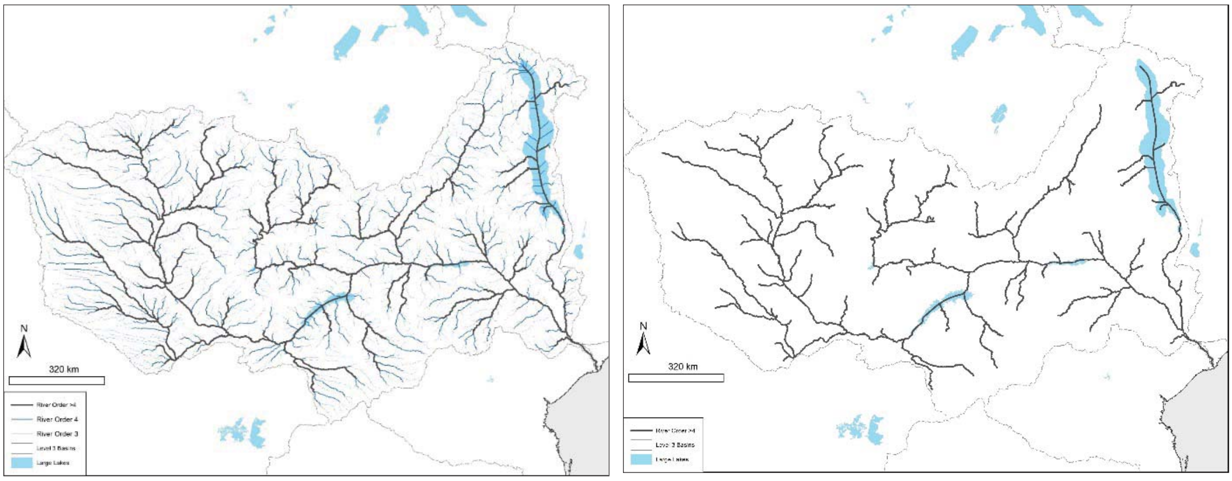


Figure A.9 Comparison of river network of the Zambezi River at River Order three and higher (left) and five and higher (right).

Datasets for climate, bioregions and ecology river ecosystem types

Three datasets that capture climate and ecosystem type in the classification were reviewed: FEOW, FEOW MHT and the Köppen-Geiger climate classification (Beck *et al.* 2018). Of these, the MHT was selected for the following reasons:

- In DRIFT, the response curves for species or guilds based on their life history strategies that have evolved to exploit the ecological niche that they inhabit. Similar niches may be found across different regions. Often, where this is the case, the species may differ but the life history strategies may be remarkably similar; and thus so too are the DRIFT response curves. Therefore, it is possible and even likely that DRIFT response curves may be extrapolated across FEOWS. Thus, basing the classification of rivers on FEOWs may limit the extrapolation of data across functionally-similar but taxonomically-different regions.
- The MHT dataset groups the 47 FEOWs in the SADC mainland into eight functionally-similar groupings, which overcomes the above-mentioned issue.
- The MHT dataset includes coarse level temperature and precipitation classifications, similar to those used in the Köppen-Geiger climate classification (e.g. temperate, tropical, xeric, montane) and therefore the additional use of Köppen-Geiger is not required.

Dataset and thresholds for longitudinal slope classification

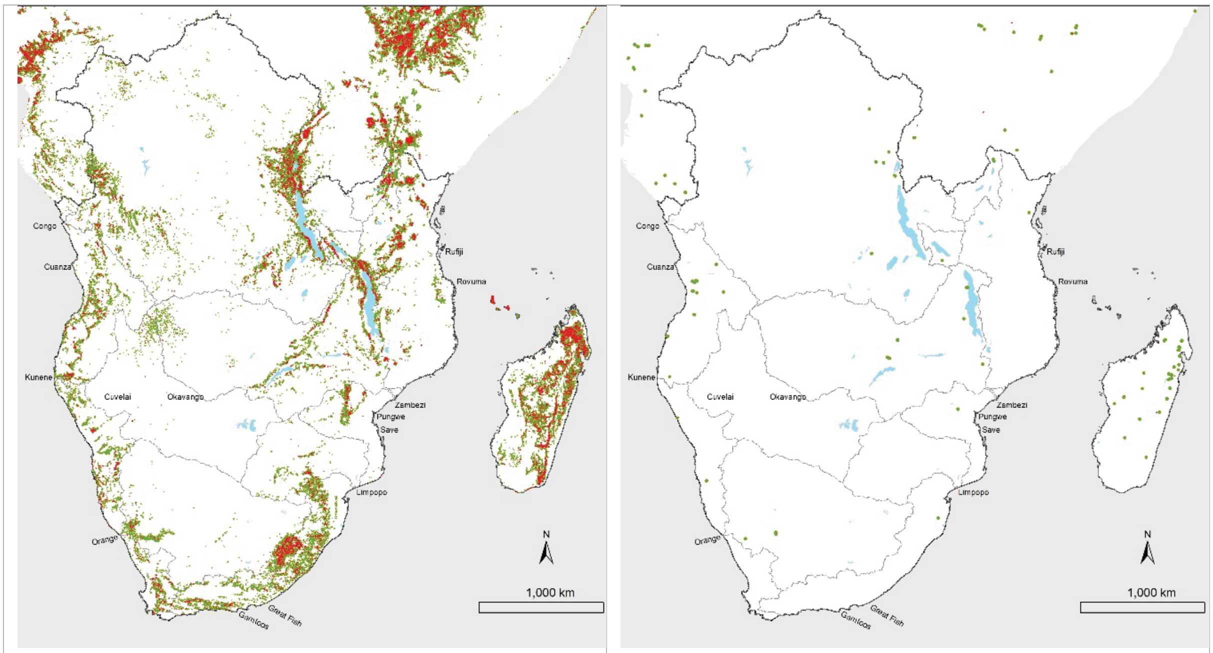
The RiverATLAS dataset includes reach average stream gradient; and further averaging is not required. Globally, the average reach length in the dataset is 4.2 km and within SADC the gradient is provided over an average reach length of 3.6 km (for River Orders ≥5).

Rowntree *et al.* (2000) proposed six river slope categories and additional rejuvenated profiles whereas Moolman (2008) applied the six main types, and NBA (Nel *et al.* 2004) used four river categories; as they lump three higher slope categories into a single 'mountain stream' category (Table A.4).

Table A.4 Slope classes and geomorphic zones per Moolman (2008) and Nel *et al.* (2004)

Slope class	Geomorphological zones Moolman (2008)	Geomorphological zones NBA (Nel *et al.* 2004)	Abbreviation
>0.1	Mountain headwater stream	Mountain stream	MS
0.04-0.1	Mountain stream		
0.02-0.04	Transitional	Upper foothills	UD
0.005-0.02	Upper foothills		
0.001-0.005	Lower foothills	Lower foothills	LF
0.0001-0.001	Lowland river	Lowland river	LL

In the river data set suggested for use (River Orders ≥5), there are no rivers with slopes > 400 decimetre per kilometre (which equates to Rowntree *et al.* 's (2000) mountain stream and mountain headwater classes combined; Figure A.10), thus the four NBA categories are suggested for use. It should be noted that high slope, high elevation rivers (such as in Lesotho and eastern DRC) are classified as Montane Freshwaters in the MHT.



Green (slopes 200 to 400 dm per km), red (slopes greater than 200 dm per km). All River orders shown

Green (slopes 200 to 400 dm per km), red (slopes greater than 200 dm per km). River orders 5 and above shown

Figure A.10 **Comparison of stream slope with order 1 to 4 (left) and those with order higher than 4 (right).**

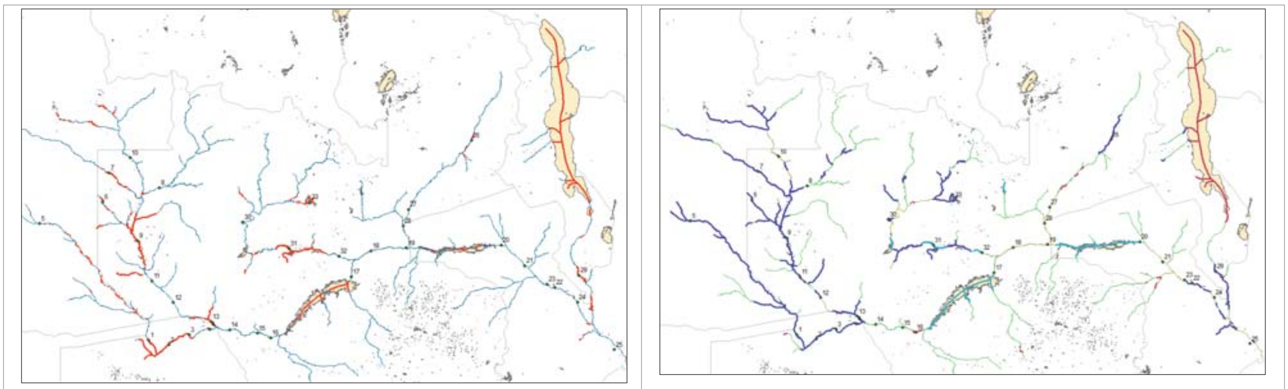
Datasets for flats and gorges

Flats (including floodplains, wetlands, marshes, flats, swamps and pans) and gorges have different ecological functioning and are modelled differently in the DRIFT framework, i.e. they have different indicators, links and response curves from each other and from other river types.

When applied to the SADC region, the RiverATLAS slopes used for Moolman (2008) and NBA (Nel *et al.* 2004) did not sufficiently demarcate these areas, although river gradient classes identified gorges to some extent. Thus, other options from the RiverATLAS dataset were evaluated in terms of the extent to which the demarcated known floorplans, wetlands and gorges in the Zambezi Basin. The layers tested included: land cover class, wetland class and terrain slope.

Land cover class did not demarcate these areas but wetland class and terrain slope identified flats to some degree, but terrain slope was better (Figure A.11):

- An average terrain slope of 0 (zero) coincided most closely with known wetlands and floodplains
- Average terrain slope ≥50 coincided most closely with known gorges, but this may be fine-tuned further.



Terrain slope = 0 identifies the Elephant Marsh (29), Kafue Flats (31), Barotse Floodplain (9), and Lukanga Swamp (33).

Wetland extent identifies the Elephant Marsh (29), Kafue Flats (31), Barotse Floodplain (9), and Lukanga Swamp (33).

Figure A.11 Coarse identification of wetlands through the use of terrain slope (top) and wetland extent (bottom) layers in RiverATLAS.

A.4.1.2 Categorisation of ZAMWIS nodes categories and those according to Slope, Major Habitat Type and Flats/Gorge

The 40 nodes in the Zambezi and Okavango basins that were used in a previous classification (ZAMWIS: Brown and Joubert 2018) were categories using the three attributes: Slope (4 categories), MHT (10 categories) and River/Flats /Gorge. The categorisation could then be compared to the way the nodes had been categorised for ZAMWIS. Note that the attributes used for the potential new typology are all available from RiverAtlas, whereas of the five used in ZAMWIS only two would have been available as shapefiles. The attributes and resulting categories according to both methods are provided in Table A.5, and the 40 nodes are displayed on a map showing the Slope-MHT categories in Figure A.12.

The first group shown in Table A.5 (LL tropical floodplain (flats)) has seven nodes, and includes river floodplain systems (Kwando, Chobe, Linyanti areas) and large wetlands / flats (Kafue flats, Elephant marshes), and it is anticipated that indicators and response curves in these systems would be similar. The second group (LL tropical floodplain) has 21 nodes, two of which were previously classified as "Swamp / floodplain systems" (Zambezi-Mana Pools and Kapoka on the Okavango). While these two locations include substantial floodplains, they are quite different to locations in the first group such as the Kafue flats, and the Chobe-Linyanti-Kwando areas. On the other hand, the Panhandle site on the Okavango, in Group 2, would more naturally fit into Group 1, and indeed the site itself is less than a kilometre below a reach classified as such. This suggests that for the classification of flats (but not gorges), an average slope over two or three reaches could be used, and / or that the slope threshold should be very slightly above 0. At least one of the sites (Node 6, Luanginga) in Group 4 (LL tropical upland) would also, probably more correctly, be regrouped into Group 3 (LL tropical upland (flats)) with this slight adjustment to the application of the criterion. Group 5, the "Tropical floodplain gorges" with various slopes, seems to be an appropriate group for extrapolation.

Table A.5 Nodes and their groups in the ZAMWIS study, as compared to and grouped by a potential typology using Slope, MHT and Flats / Gorge criteria from RiverATLAS attributes. Grey shaded nodes are in the Okavango basin, the rest in the Zambezi basin.

			ZAMWIS					Potential typology for WRC			ZAMWIS		Potential typology for WRC		
Node	River	Description	Ecoregion	Rowntree (2000)	Rosgen (1994)	Fish guilds	Wetland Vegetation	Slope	MHT	1=Flats 2=Gorge 0=Neither	#	Group in ZAMWIS	#	Potential group for WRC	Notes
M	Khwai	Xakanaka	Okavango	FP	FP	4	4	NA	NA	NA	0	Ungrouped	0	Ungrouped	Not included in river cover
G	Cuebe	Capico	Upper Zambezian headwaters	LF	C	1	2	NA	NA	NA	2	2 Meandering reaches; upper / middle Zambezi	0	Ungrouped	Not included in >=5 Strahler order
33	Kafue	Kafue-Lukanga Swamp	Kafue	NA	FP	1	1	1	10	1	0	Ungrouped	1	LL tropical floodplain (flats)	
29	Shire	Shire-Elephant Marsh	Mulanje	LL	FP	1	1	1	10	1	5	5 Swamp / floodplain systems	1	LL tropical floodplain (flats)	
31	Kafue	Kafue-KafueFlats	Kafue	LL	FP	1	1	1	10	1	5	5 Swamp / floodplain systems	1	LL tropical floodplain (flats)	
1	Kwando-Linyati	Linyanti @ Kwando	Upper Zambezi Floodplains	LL	E	1	1	1	10	1	1a	1a Zambezi headwaters	1	LL tropical floodplain (flats)	
3	Kwando-Linyati	Linyanti-Chobe-break	Upper Zambezi Floodplains	LL	E	1	2	1	10	1	1a	1a Zambezi headwaters	1	LL tropical floodplain (flats)	
9	Zambezi	Zambezi-BarotseFP	Upper Zambezi floodplains	LL	FP	1	1	1	10	1	1b	1b Zambezi headwaters	1	LL tropical floodplain (flats)	
13	Zambezi	Zambezi-Chobe Zambezi FP	Upper Zambezi floodplains	LL	FP	1	1	1	10	1	1b	1b Zambezi headwaters	1	LL tropical floodplain (flats)	
30	Kafue	Kafue@ HookBridge	Kafue	LL	C	1	2	1	10	0	0	Ungrouped	2	LL tropical floodplain	
L	Okavango	Panhandle	Okavango	FP	D	1	1	1	10	0	0	Ungrouped	2	LL tropical floodplain	Just below reach defined Flats by terrain slope
12	Zambezi	Zambezi-Ngonye to Katimo	Upper Zambezi floodplains	LL	C	1	2	1	10	0	2	2 Meandering reaches; upper / middle Zambezi	2	LL tropical floodplain	
16	Zambezi	Zambezi-Batoka to Kariba	Middle Zambezi	LF	C	1	2	1	10	0	2	2 Meandering reaches; upper / middle Zambezi	2	LL tropical floodplain	
26	Luangwa	Luangwa-South Luangwa NationalPark	Middle Zambezi	LL	C	1	2	1	10	0	2	2 Meandering reaches; upper / middle Zambezi	2	LL tropical floodplain	
K	Okavango	Popa Falls	Okavango	UF	A	1	2	1	10	0	2	2 Meandering reaches; upper / middle Zambezi	2	LL tropical floodplain	
11	Zambezi	Zambezi-Barotse to Ngonye	Upper Zambezi floodplains	LL	DA	1	1	1	10	0	3	3 Braided reaches; lower Zambezi	2	LL tropical floodplain	
14	Zambezi	Zambezi-Kazangulu to Victoria Falls	Upper Zambezi floodplains	LL	C	1	1	1	10	0	3	3 Braided reaches; lower Zambezi	2	LL tropical floodplain	
22	Zambezi	Zambezi-Tambara MobileSands	Lower Zambezi	LL	DA	1	1	1	10	0	3	3 Braided reaches; lower Zambezi	2	LL tropical floodplain	
18	Zambezi	Zambezi-Mana Pools	Middle Zambezi	LL	FP	1	1	1	10	0	5	5 Swamp / floodplain systems	2	LL tropical floodplain	
J	Okavango	Kapoka	Okavango	LL	FP	1	1	1	10	0	5	5 Swamp / floodplain systems	2	LL tropical floodplain	
21	Zambezi	Zambezi-Tete MobileSands	Lower Zambezi	LL	D	1	1	1	10	0	6	6 Lower Zambezi mainstem	2	LL tropical floodplain	
23	Zambezi	Zambezi-LupataGorge	Lower Zambezi	LF	F	1	2	1	10	0	6	6 Lower Zambezi mainstem	2	LL tropical floodplain	2km below a reach defined Gorge by terrain slope.
24	Zambezi	Zambezi-Chemba Anabranch	Lower Zambezi	LL	D	1	1	1	10	0	6	6 Lower Zambezi mainstem	2	LL tropical floodplain	
25	Zambezi	Zambezi-Delta	Lower Zambezi	LL	D	1	1	1	10	0	6	6 Lower Zambezi mainstem	2	LL tropical floodplain	
2	Kwando-Linyati	Linyanti FP	Upper Zambezi Floodplains	LL	FP	1	1	1	10	0	1b	1b Zambezi headwaters	2	LL tropical floodplain	Between two reaches defined Swamp by terrain slope
4	Kwando-Linyati	Linyanti-Chobe Zambezi FP	Upper Zambezi Floodplains	LL	FP	1	1	1	10	0	1b	1b Zambezi headwaters	2	LL tropical floodplain	
7	Lungwebungu	Lungwebungu	Zambezian headwaters	LL	E	1	1	1	9	1	1a	1a Zambezi headwaters	3	LL tropical upland (flats)	

			ZAMWIS					Potential typology for WRC			ZAMWIS		Potential typology for WRC		
Node	River	Description	Ecoregion	Rowntree (2000)	Rosgen (1994)	Fish guilds	Wetland Vegetation	Slope	MHT	1=Flats 2=Gorge 0=Neither	#	Group in ZAMWIS	#	Potential group for WRC	Notes
8	Kabompo	Kabompo @ Watopa Pontoon	Zambezian headwaters	LL	C	1	2	1	9	0	2	2 Meandering reaches; upper / middle Zambezi	4	LL tropical upland	
10	Zambezi	Zambezi Upper	Zambezian headwaters	LL	C	1	2	1	9	0	2	2 Meandering reaches; upper / middle Zambezi	4	LL tropical upland	
H	Cubango	Mucundi	Upper Zambezian headwaters	LL	C	1	2	1	9	0	2	2 Meandering reaches; upper / middle Zambezi	4	LL tropical upland	
5	Kwando	Kwando Upper	Zambezian headwaters	LL	E	1	1	1	9	0	1a	1a Zambezi headwaters	4	LL tropical upland	
6	Luanginga	Luanginga	Zambezian headwaters	LL	E	1	1	1	9	0	1a	1a Zambezi headwaters	4	LL tropical upland	Just below a reach marked as Flats by terrain slope.
I	Cuito	Cuito Cuanavale	Upper Zambezian headwaters	LL	E	1	2	1	9	0	1a	1a Zambezi headwaters	4	LL tropical upland	
15	Zambezi	Zambezi-BatokaGorge	Middle Zambezi	LF	A	1	3	3	10	2	4	4 Steep gorges	5	UF tropical floodplain (gorge)	
17	Zambezi	Zambezi-Kariba Gorge	Middle Zambezi	LF	B	1	3	1	10	2	4	4 Steep gorges	5	LL tropical floodplain (gorge)	
20	Zambezi	Zambezi-Mpanda Nkua	Lower Zambezi	LF	B	1	3	1	10	2	4	4 Steep gorges	5	LL tropical floodplain (gorge)	
27	Luangwa	Luangwa-NdevuGorge	Middle Zambezi	UF	A	1	3	2	10	2	4	4 Steep gorges	5	LF tropical floodplain (gorge)	
32	Kafue	Kafue-KafueGorge	Kafue	MS	Aa+	1	3	4	10	2	4	4 Steep gorges	5	MS tropical floodplain (gorge)	
19	Zambezi	Zambezi-Mupata Gorge	Middle Zambezi	LF	F	1	2	1	10	2	6	6 Lower Zambezi mainstem	5	LL tropical floodplain (gorge)	
28	Luangwa	Luangwa-Katondwe	Middle Zambezi	LF	D	1	2	1	10	2	6	6 Lower Zambezi mainstem	5	LL tropical floodplain (gorge)	

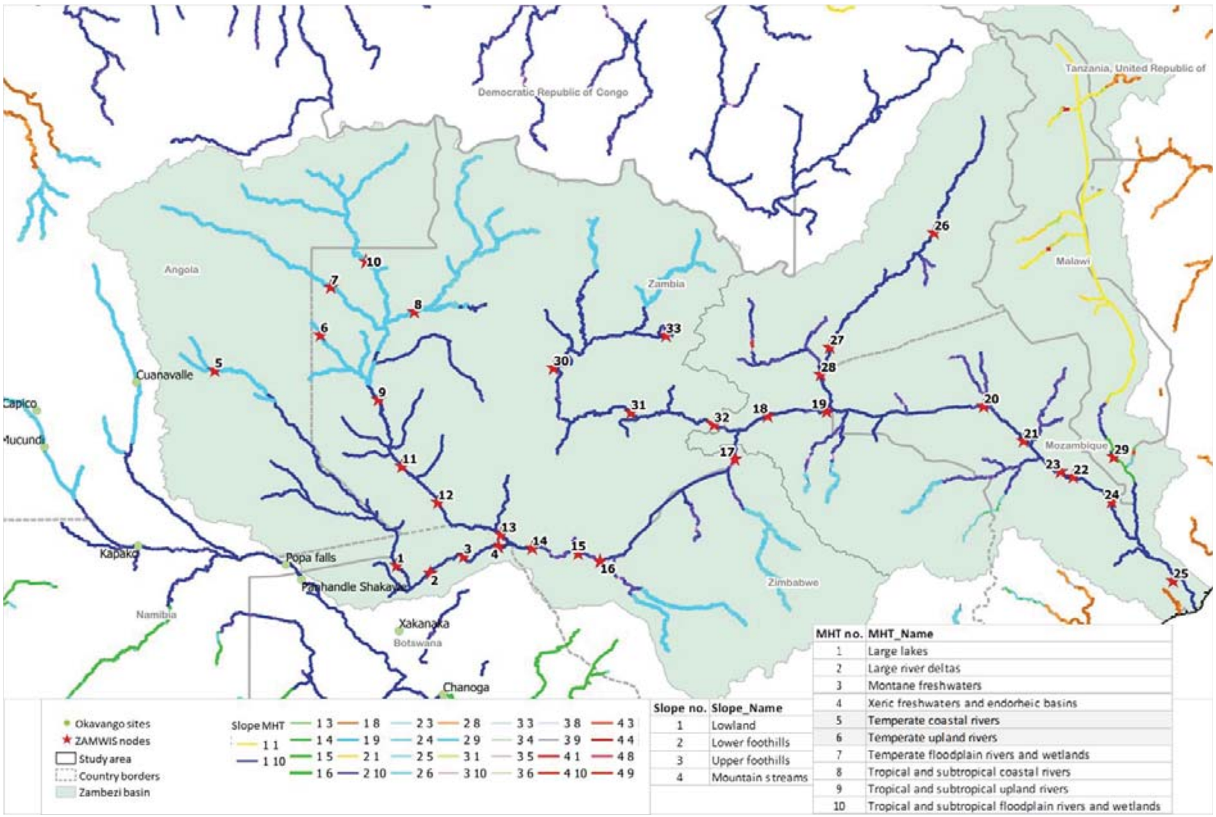


Figure A.12 **Zambezi Basin and sites used in ZAMWIS showing their location on reaches coloured according to Slope and MHT. The Slope-MHT numbers are 1 to 4 for slope and 1 to 10 for MHT and are explained in the keys (MHTs shaded grey in the key are not present in the map).**

A.4.1.3 Summary

The results of this exercise suggest that the assessments in this project should be limited to rivers of stream order ≥5, and that these can be classified (Figure A.13) in a manner that is compatible with the extrapolation of existing DRIFT data sets using:

- The 9 MHT types
- NBA's 4 slope classes,
- overlaid with flats and gorges as determined through terrain slope.

It was not possible to determine additional categories, such as whether the reach is perennial or non-perennial or whether it is a "flashy" or "flood pulse" system, using the layers examined thus far. While there are attributes within the RiverAtlas that may help differentiate between perennial and non-perennial rivers, there do not seem to be any that indicate flashy / flood pulse flow regimes.

Based on the variables discussed the theoretical number of river ecosystem classes are 108 (4 x 9 x 3), not considering the distinction of mainstem vs tributary rivers (Table A.6). These classes should be considered for a scaled approach at an SADC level, compared to a country-wide or selected basin level.

Table A.6 **Number of classes per variable considered for typing rivers in SADC.**

Variable	Classes	Notes
Longitudinal geomorphic zones	4	The NBA 2011 and 2018 used four longitudinal geomorphic zone classes
Climate and ecology	9	MHT has 9 classes in SADC
Valley profile	3	Rivers, flats, gorges

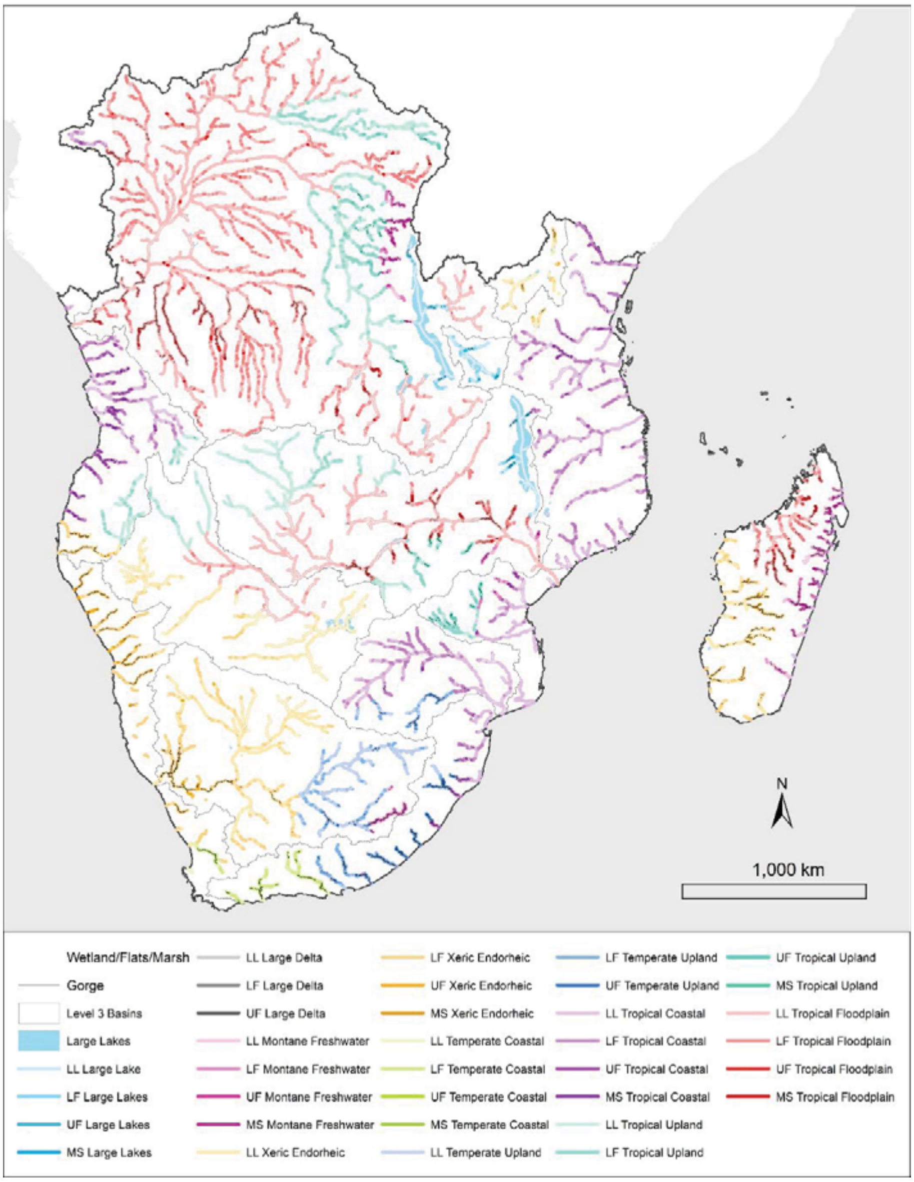


Figure A.13 **Results of typing exercise using four slope categories, MHT and terrain slope to demarcate swamps and gorges.**

A.5. Typology for major SADC estuaries

Estuaries are a challenge to delineate and classify because they vary temporally in shape and size and encompass a gradient in environmental conditions from riverine to marine (Van Niekerk *et al.* 2021; 2023b). Anthropogenic impacts and morphological changes brought about by climate and sea level fluctuations further complicate the process.

The classical definition of an estuary is a "*semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater derived from land*" (Cameron and Pritchard 1963; Pritchard 1967; Elliott and McLusky 2002). However, these definitions do not recognise that local estuaries may not necessarily have a 'free connection with the sea' but are 'either permanently or periodically open to the sea' (Day 1980; CSIR 1992; Whitfield and Elliott 2011). In addition, although Fairbridge (1980) proposed setting the tidal limit as the upstream extent of an estuary, there are examples in Southern Africa where back-flooding under closed-mouth conditions and/or the inland limit of salinity penetration represents the upstream boundary (Van Niekerk *et al.* 2013). Given the high diversity of estuary types in Southern Africa, for this study the more inclusive definition used for South Africa was adopted regionally in which an estuary is (Van Niekerk *et al.* 2013; 2020): *"a partially enclosed permanent water body, either continuously or periodically open to the sea that extends as far as the greater of the upper limit of tidal action, salinity penetration or back-flooding under closed mouth conditions. During high catchment inflows an estuary can become a river mouth with no seawater entering the estuarine area or, when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become fresh or hypersaline".* Coastal bodies that dry out (ephemeral systems) or no longer connect to the sea (Freshwater Coastal Lakes) are excluded from the systemic assessment but will be noted where they occur.

'Typology' here refers to the characterisation of estuary types according to shared key features; whereas 'ecosystem classification' refers to the categorising of estuarine ecosystem types based on their abiotic (e.g. climate, oceanic conditions, substrate, water and all other non-living elements) and biotic constituents (Allee *et al.* 2000). Ecosystem classifications are often complex, hierarchical or nested; typologies tend to be more straightforward, based on general type. The level of classification depends mainly upon the number of criteria selected (e.g. biogeography, geomorphology, and biology) and the spatial resolution required (e.g. local, regional, or global).

Over the past six decades estuary classification studies have evolved from relatively simple 'topology' schemes (defining estuary types based on a key process or feature) to more complex regional ecosystem-level classification schemes (regional schemes that include elements of climatic/biogeography, estuarine processes, biological responses) (Van Niekerk *et al.* 2020). The greater the number of criteria and the wider the geographical scope, the more complex becomes the classification. Depending on the task or information required, a balance needs to be established between the number of criteria and the level of detail selected (Whitfield and Elliott 2011). The choice of classification system thus largely depends on its intended purpose.

Globally, numerous estuary typology and classification schemes exist but many are specific to a geographic region (Whitfield and Elliott 2011). Traditionally, estuaries have been typed based on key processes and features such as tidal range, tidal prism, topography, geomorphology, salinity characteristics and ecosystem energetics (e.g. Davies 1964; Nichols and Biggs 1985; Kennish 1986). Topographical typologies categorize estuaries as drowned river valleys, fjords, bar-built estuaries, and others (Pritchard 1952; Dyer 1997), while morphological typologies are based on physical features resulting from the interplay between catchment runoff, sediment loads, and tides, waves and other coastal processes (Dalrymple *et al.* 1992). Salinity-based approaches separate estuaries according to the degree of mixing within the water column (Pritchard 1955; Cameron and Pritchard 1963) and stratification-circulation typologies use densiometric numbers from fluid mechanics (Hansen and Rattray 1966; Fischer 1972; Simpson *et al.* 1990). Most of these typologies require extensive in-field time series and high spatial coverage data and are thus not appropriate for use in this study.

National or regional ecosystem-level classification schemes need to recognise that environmental parameters are often not strongly reflected in physical and morphology typologies, such as variations in climate, biogeography or vegetation (see Whitfield and Elliott 2011 for the evolution of estuary classification). Examples include the comprehensive United States marine and estuarine ecosystem and habitat classification that moves from a biogeographical to a habitat scale (Allee *et al.* 2000). Regional schemes that explicitly include Intermittently closed estuaries, common on the South African coastline, are those of Australia and California. Early Australian schemes identified seven geomorphology-based estuary types across five biogeographical regions under the influence of wave, tide and river energy (Boyd *et al.* 1992; Dalrymple *et al.* 1992; Kench 1999). Linking these to climate and rainfall characteristics allowed for the incorporation of freshwater- and evaporation-dominated types (Boyd *et al.* 1992; Heggie *et al.* 1999a; 1999b; Kench 1999). A more recent Australian classification described three intermittently open/closed estuary types (IOCE) based on the duration and frequency of mouth condition and estuary size (large, medium or small) (McSweeney *et al.* 2017). A typology of Californian estuaries distinguished eight closed-mouth states based on berm elevation and tidal exchange where river inflow rather than tidal influence controls mouth opening. This scheme recognised that mouth states prevail over multi-year to multi-decadal time frames (Jacobs *et al.* 2010). Recently South Africa updated their estuary classification system to recognised nine estuary types and four biogeographical regions (van Niekerk *et al.* 2020). Van Niekerk *et al.* (2008) also explored the development of a broad classification for the Benguela Current Large Marine Ecosystem, which includes the ephemeral systems that occurred along the west coast of Southern Africa.

For the purposes of developing a typology for Southern Africa estuaries, the international IUCN GET and regional South African Estuary Typology were considered most appropriate and are discussed in greater detail below.

A.5.1. International: IUCN Global Ecosystem Typology

The IUCN has recently published a new global typology for ecosystems (Keith *et al.* 2020). The typology comprises a nested hierarchy of units (Figure A.14) to facilitate application at different organisational scales and enable integration of existing classifications where possible. Groupings in three upper levels of the typology represent ecosystems that share functional properties, irrespective of the biota engaged in the functions. The units of these upper levels were developed from the top-down, with a successive division to ensure global consistency and comprehensive coverage. Estuaries represented a challenge for the authors and are considered in two realms (Freshwater/Marine and Marine/Freshwater/Terrestrial) at level 1 and two biomes (FM1 Transitional waters and MFT1 Brackish tidal systems) at level 2 (Keith *et al.* 2020). More useful to the Southern African estuary classification are the third tiered level of the hierarchical classification system, the ecosystem functional groups (EFGs) [5] that defines four key estuary archetypes categorised based on geomorphology, mouth states, and depositional rates (Table A.7). *FM1.1 Deepwater coastal inlets (mostly fjords)* are semi-confined aquatic systems with many features of open oceans with strong influences from adjacent freshwater and terrestrial systems that produce striking environmental and biotic gradients but are not relevant to the study area.

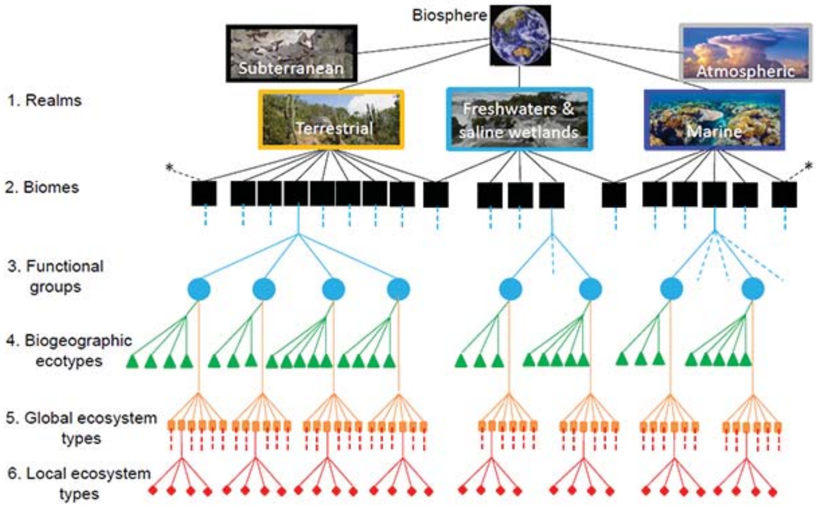


Figure A.14 **IUCN Global Ecosystem Typology comprises six hierarchical levels. Three upper levels – realms, functional biomes and ecosystem functional groups – classify ecosystems based on their functional characteristics (such as structural roles of foundation species, water regime, climatic regime or food web structure. The three lower levels of classification – biogeographic ecotypes, global ecosystem types and sub global ecosystem types – are often already in use and incorporated into policy infrastructure at national levels and can be linked to these upper levels (Source: Keith *et al.* 2020).**

---

[5] *Ecosystem functional group: A group of related ecosystems within a biome that share common ecological drivers promoting convergence of biotic traits that characterise the group. Functional groups are derived from the top-down by subdivision of biomes.*

Table A.7 International Union for Conservation of Nature (IUCN) Global Ecosystem Typology ecosystem types relevant South African Development Community (SADC)

REALM	BIOME	FUNCTIONAL GROUP (ECOTYPE)
Freshwater/Marine	FM1 Transitional waters	FM1.1 Deepwater coastal inlets
Freshwater/Marine	FM1 Transitional waters	FM 1.2 Permanently open riverine estuaries and bays
Freshwater/Marine	FM1 Transitional waters	FM 1.3 Intermittently closed coastal lagoons
Marine/Freshwater/Terrestrial	MFT1 Brackish tidal systems	MFT 1.1 Coastal river deltas

FM 1.2 Permanently open riverine estuaries and bays are mosaic systems characterized by high spatial and temporal variabilities in structure and function, which depend on coastal geomorphology, ratios of freshwater inflows to marine waters and tidal volume (hence residence time of saline water), and seasonality of climate. Water-column productivity is typically higher than in nearby marine or freshwater systems. *FM 1.3 Intermittently closed coastal lagoons* have high spatial and temporal variability in structure and function, which depends largely on the status of the lagoonal entrance as open or closed. Communities generally have low species richness when compared to those of permanently open estuaries (FM1.2) because estuary mouth closure prevents entry of marine organisms and resident biota must tolerate significant variation in salinity, inundation, dissolved oxygen and nutrient concentrations. Resident communities are dominated by opportunists, with relatively short life cycles. *MFT 1.1 Coastal river deltas* are prograding depositional systems, shaped by freshwater flows and influenced by wave and tidal flow regimes and substrate composition. The biota of these ecosystems reflects strong relationships with terrestrial, freshwater and marine realms at different spatial scales. Ecosystem Functional Groups FM1.2, FM1.3 and MFT 1.1 is the dominant types in SADC. The GET also allows for the typing of estuarine-associated habitats, e.g. mangroves (MFT1.2 Intertidal forests and shrublands), saltmarshes (MFT 1.3 Coastal saltmarshes) and seagrass (M1.1 Seagrass meadow).

Level 4 of the GET is represented by **Biogeographic ecotypes** which are ecoregional expressions of an ecosystem functional group (level 3). They are proxies for compositionally distinctive geographic variants that occupy different areas within the global distribution of a functional group. While Level 5 are Global ecosystem types representative of complexes of organisms, with similar ecological processes and their associated physical environment within an area occupied by an ecosystem functional group, but with substantial differences in the composition of organisms. They are derived from the bottom-up (national or regional), either directly from ground observations or by aggregating the lowest level, the Subglobal ecosystem types (level 6). A highly detailed level 5 and 6 classifications can require significant data input and resources to develop.

Given the high diversity of estuary types occurring along the Southern African coastline, however, it is proposed that refinement of the Level 3 Ecosystem Functional Groups in combination with

biogeography be used to build the Estuary Ecosystem Classification for the region, i.e. develop a level 5 or 6 ecosystem classification that can be nested in level 3 of the GET.

A.5.2. South Africa's Estuary Typology

Based on an analysis of the physical characteristics of estuaries and their associated catchments, South Africa's 290 estuarine systems have been categorised into nine functional types, namely Estuarine Lake, Estuarine Bay, Estuarine Lagoon, Predominantly Open, Large and Small Temporarily Closed, Large and Small Fluvially Dominated, and Arid Predominantly Closed (Van Niekerk *et al.* 2020).

A.5.3. Key Characteristics Influencing Classification

Drawing on the IUCN GET and South African typology approaches three key elements are considered relevant in the Estuarine Ecosystem Typology for Southern Africa, that is:

- Biogeographical regions
- Tidal ranges
- Functional type.

A.5.3.1 Biogeographical Regions

For the purposes of developing a Southern African Estuary Classification system, the coastal zone is defined as the region from the northern border of Angola on the West Coast to the northern Tanzanian border on the East Coast of Africa: a mainland coastline of ~8 600 km (Potts *et al.* 2015). The five countries along this coastline have diverse physical and climatic coastal features. The 1 650 km Angolan coastline has about 33 estuaries and one large embayment, Baia dos Tigres (Van Niekerk *et al.* 2008). The Namibian coast, 1 570 km long, is relatively straight and due to very low rainfall, there are two only permanent open estuaries, the Cunene and Orange, which border Angola and South Africa, respectively (van Niekerk *et al.* 2008). The South African coastline extends for 3 650 km and has about 290 estuaries (van Niekerk *et al.* 2020). The Mozambique coastline, 2 700 km in length, is characterized by a wide diversity of habitats. Mozambique has over 100 estuaries with well-developed mangrove forests. Tanzania has a coastline of about 800 km and there are at least 12 large estuaries along its coast. The coastline of Madagascar is 5 600 km in length with over 20 large estuaries documented. Most of the estuaries listed above are not spatially represented or delineated. It is the intent of this project to capture the information spatially.

Four major ocean currents – the Angola, Benguela, Agulhas and East African coastal currents – dominate the region resulting in complex biogeographical zonation for the region (Potts *et al.* 2015) provided an overview of the biogeographic zonation of the Southern African coastline based on the estuarine fauna. According to this zonation, Angola (warm-temperate, subtropical, and tropical) and South Africa (cool-temperate, warm temperate and sub-tropical) host three biogeographic zones, Namibia (warm-temperate and cool-temperate) and Mozambique (sub-tropical and tropical) two, and Tanzania (tropical) one Madagascar is largely topical.

However, for the Southern African Estuary Typology, the coastal biogeographical regions were refined. This was first achieved by coastal areas by 100 km, and then dividing it into zones, based on the extent described by Potts *et al.* (2015) but updated with the four types of biogeographical regions derived for South Africa, that is tropical, subtropical, warm, and cool temperate (Van Niekerk *et al.* 2020). Additional information was also sourced on biogeographical regions in Madagascar (Fiona MacKay, Oceanography Research Institute, unpublished data) with most global literature suggesting that Madagascar fall within a tropical biogeographical region (Figure A.15), however recent unpublished studies show a potential tropical-subtropical divide along part of the south tip of the island.

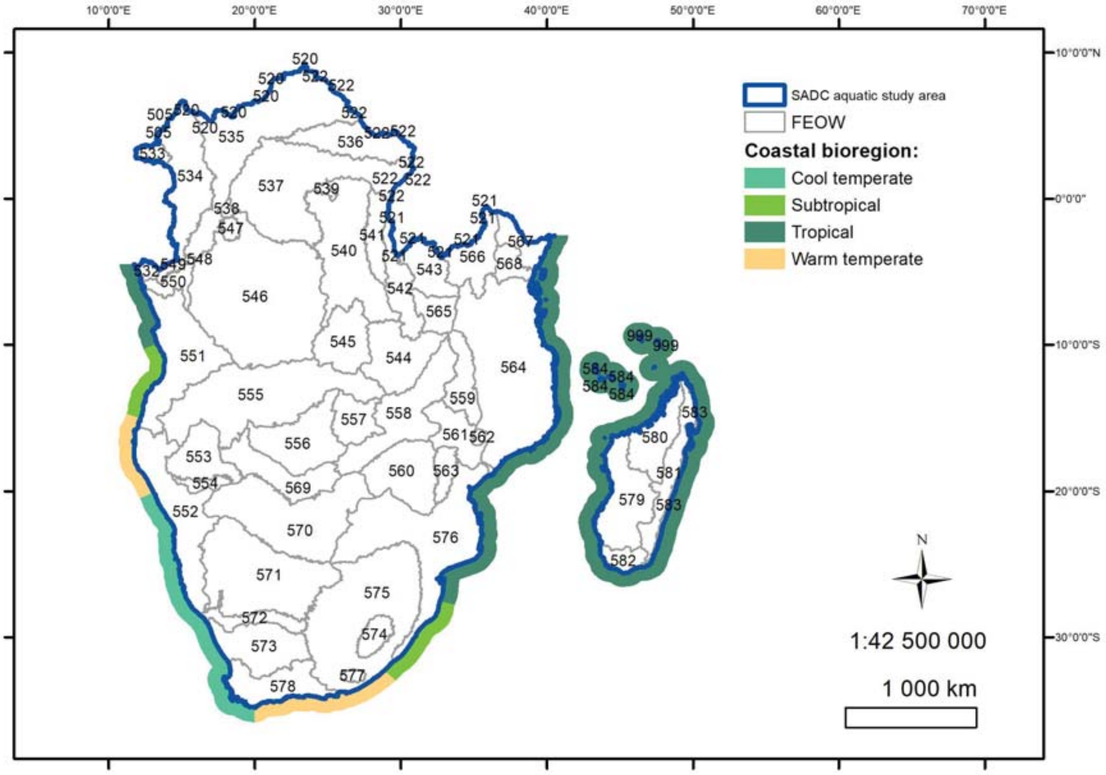


Figure A.15 Refined biogeographical zonation of coastal regions in SADC (adapted from: Potts *et al.* 2015)

A.5.4. Identification and Classification of Coastal Outlets

To identify possible locations of outlets along the coast the Strahler orders (1-9) from the HydroRIVERS (Linke *et al.* 2019) and the FEOW regions (20 types) for Southern Africa (Abell *et al.* 2008) were applied along the coast. Note that the river orders as not associated with the river flow but are indicative of the number of tributaries that can contribute to a river. Using this process, 2 469 outlets along the Southern African coast were identified (Table A.8). Figure A.16 displays the distribution of river orders across the various biogeographical regions.

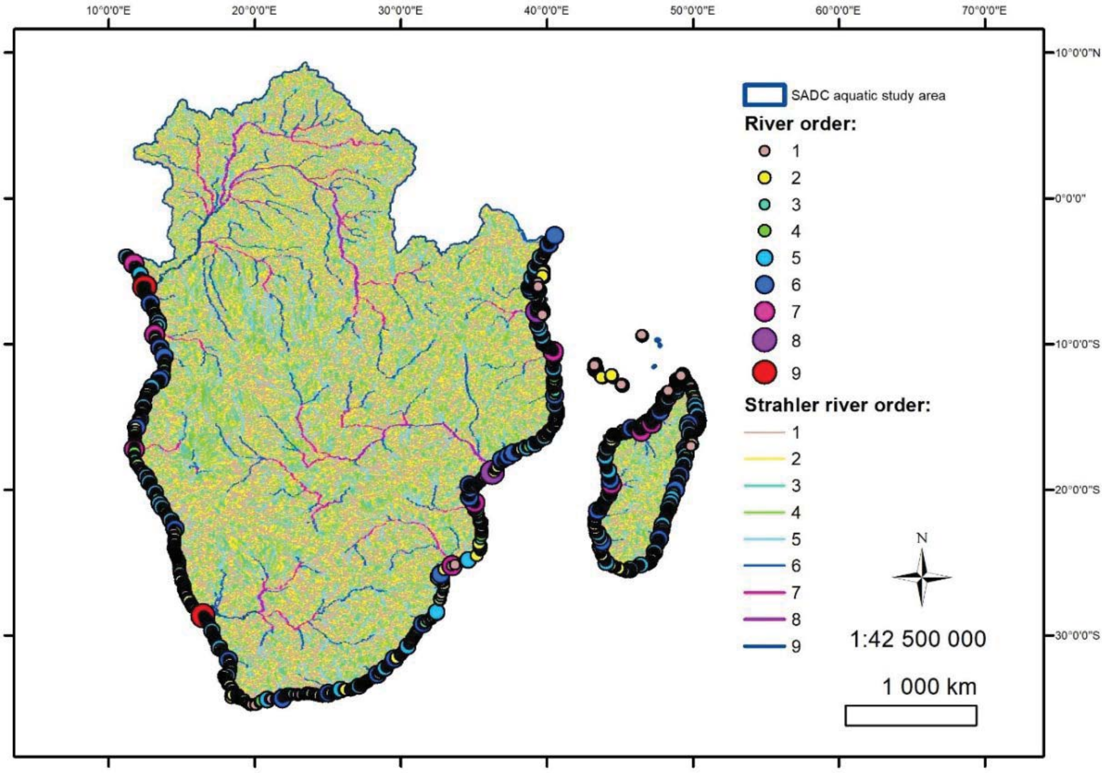


Figure A.16 **Estuarine outlets captured along the coastal boundary of Southern Africa as informed by Strahler order of the HydroRIVERS (Linke *et al.* 2019)**

Table A.8 **Summary of identified coastal outlets per Strahler River order and biogeographical region**

STRAHLER RIVER ORDER	**BIOGEOGRAPHICAL REGION**				**GRAND TOTAL**
	Cool temperate	Subtropical	Tropical	Warm temperate	
1	181	111	936	106	1334
2	84	50	415	73	622
3	45	24	181	31	281
4	16	17	95	13	141
5	7	7	52	6	72
6	2	5	22	4	33
7			8	1	9
8			2		2
9	1		1		2
Grand Total	**336**	**214**	**1712**	**234**	**2496**

To classify systems, outlets were first inspected to determine their Strahler River Order, size and shape of the basin, and mouth behaviour, i.e. permanently open or closed in some imagery. All estuaries investigated had at least two historical photo periods, with systems situated near developed areas often having >5 images. The photo record typically covered the past 10 to 20 years. Deltas were relatively easy to identify given their multi-channel nature and the visible accumulation of sediments seaward of the surrounding shoreline. All outlets that remained open were assigned one of the permanently open categories using the key features. Permanently open and Fluvially dominated systems are on a continuum and not always easy to distinguish, in most cases the presence of shallow, meandering/braided channels and highly turbid water column for parts of the year was used to distinguish the latter. Estuarine Bays and Estuarine Lagoons were identified through a combination of topography (e.g. presence of a marine embayment) and low river inflow; with the latter typically being more constraint, shallower, sandy and with very little freshwater inputs. Freshwater Coastal and Estuarine Lakes were identified by their relatively large, round shapes, with the latter having a clear connection to the sea at times, while Freshwater Coastal Lakes remain permanently closed from the sea by the presence of a frontal dune system.

Each outlet was the visually evaluated using available satellite imagery from Google Earth Pro and ESRI World Imagery assigned an estuary functional type based on geomorphology (size and shape), mouth state, tidal regime, biogeographical regions and FEOW zonation. The key physical features used to assign types are summarised in Table 2.4. In addition, online maps were also interrogated for the location of the major River Deltas and Permanently open estuaries occurring in Southern Africa.

Intermittently open/closed estuaries are a highly dynamic type characterised by periodic mouth closure to the sea and are found to be widespread in the region. This estuary type predominantly occurs along microtidal to low mesotidal coastlines in the mid-latitudes and predominantly on coasts with temperate climates. Similar to this study, McSweeney *et al.* (2017) mapped the global distribution of a high number of Intermittently Closed/Open Lakes and Lagoons (ICOLLs) using Google Earth online virtual globes and supplemented with literature. The coastlines of the world were inspected, and every estuary was viewed using historic aerial imagery. If an estuary was observed to be both open and closed in the historical aerial photograph record it was classified as an intermitted closed. McSweeney *et al.* (2017) captured 379 closed estuaries for SADC, with 271 for the mainland and 108 for Madagascar (Figure A.17).

Together with the South African estuary ecosystem classification (Van Niekerk *et al.* 2020), this will assist with the identification of a high number of estuaries that can close in the region. However, due to geographical displacements in the data sets, the merging of information is being done manually working from the higher river orders to the lowest. Linking intermittently closed systems to river orders also assists in identifying systems overlooked by McSweeney *et al.* 2017. Efforts were made to separate the larger Estuarine Lake type systems from the smaller intermitted open/close systems in the SADC dataset.

Using available data and the above as a visual guide, a functional type was assigned to each of the Strahler River Orders 6 and 9 outlets to allow for the development of the Southern African Estuary Classification system. Most of the higher order rivers were associated with Permanently open, Fluvially dominated or River Delta type systems.

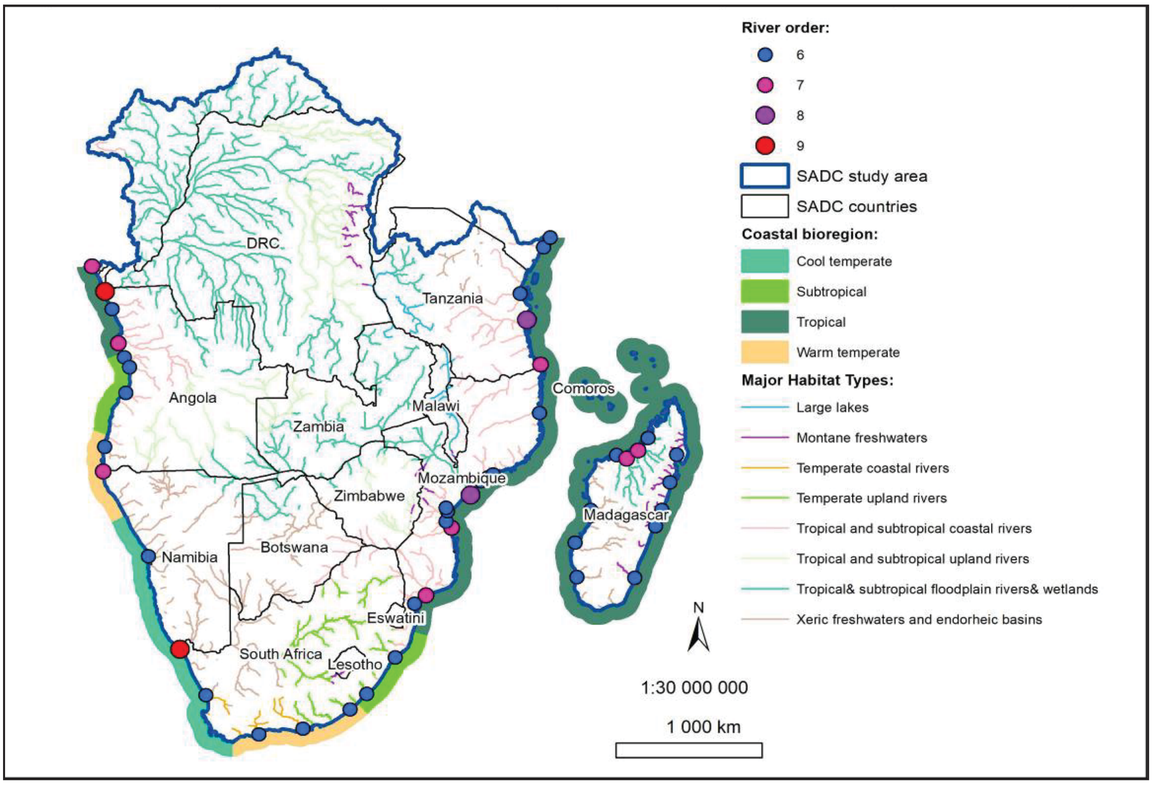


Figure A.17 **The distribution of Intermittently Closed/Open Lakes and Lagoons (ICOLLs) in Southern Africa (from McSweeney *et al.* 2017).**

Some provisional typing has also been done for the lower river order outlets (1-5), but not all systems were assigned a category. Visual inspection was essential in assigning functional types to these systems as in addition to river inflow, coastal topography plays a significant role in the size and shape of systems. Strahler River Orders 5 and 6 mostly feed into medium to large size estuaries, with most of the outlets associated with Permanently open, Fluvially dominated, Intermittently closed or Estuarine Lake type systems. Thus, a key challenge is the dearth of Google Earth imagery along sparsely populated parts of the Republic of Congo and Angola, with some estuaries only having two sets of very poor resolution images available to confirm the mouth state.

Strahler River Orders 3 and 4 outlets tend to result in ephemeral type systems along the more Xeric parts of the Southern African coast (e.g. Namibia and southern Angola), but could potentially support small to medium estuaries in the tropical and subtropical regions. While regional climatology and African datasets could guide the assigning of functional types to each estuary, visually inspection was essential in this highly variable group. The McSweeney *et al.* (2017) ICOLLs dataset also assisted in supplementing some of the observed mouth behaviour.

Strahler River Orders 1 and 2 in most cases do not represent significant freshwater inputs and result mostly in ephemeral outlets or coastal seeps that are of little value from an estuarine perspective. However, the exception here is parts of the coastal plain of Mozambique where this type of system often fed into highly complex estuarine lake systems (and in some cases Freshwater Coastal Lakes that do not open to the sea). Some River Order 1 and 2 outlets were also associated with Estuarine Lagoons. In contrast, Estuarine Bays were associated with outlets varying between river orders 1 to 6. Coastal topography was a key feature in determining the presence of this relative rare estuarine type supported by and/or expert opinion. Outlets that represent waterfalls are in the process of being removed from the datasets using slope or topography as an indicator.

A broad overview of the functional types shows that the Strahler River Orders is not a good predictor of estuary functional type (Table A.9). This is likely because most of the higher-order rivers are associated with very high runoff. For a more detailed analysis efforts will need to be made to link functional type to river inflow. The Intermitted Closed and Ephemeral functional types listed Table A.9was associated with the Xeric regions of the continent, again affirming the need for runoff data as an additional predictor of estuary functional type.

Table A.9 Comparison of estuary functional types and Strahler River Orders

FUNCTIONAL TYPE	STRAHLER RIVER ORDERS				GRAND TOTAL
	6	7	8	9	
River Delta	2	1	2	1	6
Permanently open	21	6			27
Fluvially dominated	4	1		1	6
Estuarine Lake / Permanently open Complex					2
Estuarine Bay	2	1			3
Intermitted closed	1				1
Ephemeral	1				1
Grand Total	**33**	**9**	**2**	**2**	**46**

All six River Deltas and 20 of the 27 Permanently Open systems occur in the tropical region (Table A.10). Interestingly, Fluvially Dominated types are distributed across all biogeographical regions, indicating that soil type/geology and topography are possibly a better predictor of this functional type than biogeographical region. The Intermitted Closed and Ephemeral functional types were associated with the warm and cool temperate biogeographical regions, which in turn are associated with lower rainfall regimes.

Table A.10 Distribution of estuary functional types across biogeographical regions in Southern Africa

FUNCTIONAL TYPE	BIOGEOGRAPHICAL REGION				TOTAL
	Cool temperate	Warm temperate	Subtropical	Tropical	
River Delta				6	6
Permanently open	1	3	3	20	27
Fluvially dominated	1	1	2	2	6
Estuarine Lake/Permanently open Complex				2	2
Estuarine Bay				3	3
Intermitted closed		1			1
Ephemeral	1				1
Grand Total	**3**	**5**	**5**	**33**	**46**

No significant pattern was observed in relation to tidal regimes for the larger river systems represented here by Strahler River Orders 6 to 9 (Table A.11). This is likely because in estuaries fed by major rivers fluvial processes dominate over tidal processes. The role of tidal processes is more likely to emerge in association with lower river orders.

Table A.11 Distribution of estuary functional types across tidal ranges in Southern Africa

FUNCTIONAL TYPE	TIDAL RANGE			TOTAL
	Macrotidal	Mesotidal	Microtidal	
River Delta	1	4	1	6
Permanently open	4	11	12	27
Fluvially dominated	1	1	4	6
Estuarine Lake / Permanently open Complex			1	2
Estuarine Bay	1	1	1	3
Intermitted closed			1	1
Ephemeral			1	1
Grand Total	8	17	21	46

A.5.4.1 Tidal Ranges

The tidal range is the difference in height between high tide and low tide in the sea or an estuary. Tidal range depends on time and location. The typical tidal range in the open ocean is about 0.6 m. Closer to the coast, this range is much greater. Coastal tidal ranges vary globally and can differ anywhere from near zero to over 16 m. The exact range depends on the topography of the coastline, water depth, shoreline configuration, and size of the ocean basin. Local topography can act as a 'funnel' amplifying the tide. Along such funnel-shaped coastlines, tidal waters spread across a large area in the open ocean and get concentrated in a much smaller area at the coast as the tide moves into this more restricted space and amplifies its height. Another factor affecting the tidal range is the size of the ocean basin in which the tides are located. The tidal range has been classified (Masselink and Short 1993) as (Figure A.18):

- Microtidal – when the tidal range is <2 m.
- Mesotidal – when the tidal range is between 2 and 4 m.
- Macrotidal – when the tidal range is >4 m.

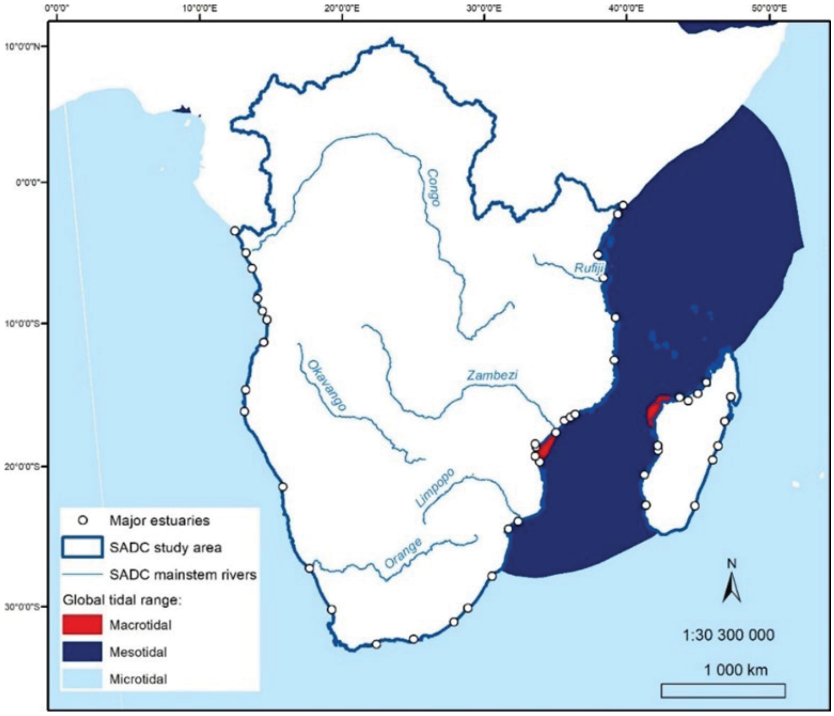


Figure A.18 **Tidal ranges for the Southern Africa coastline (Source: ESRI global tidal ranges)**

The tidal range is a key predictor of estuary mouth state and thus estuary functional type (Hayes and Fitzgerald 2013). For example, intermittently closed estuaries do as a rule does not occur on macrotidal coasts (tidal ranges >4 m) because wave action is not focused long enough at a single tide level to form the island, and strong tidal currents associated with such large tides transport the available sand to offshore linear tidal ridges. Intermittently closed estuaries are most prevalent on microtidal coasts; however, some are found in low-mesotidal settings – particularly where corresponding river flow is very low or extremely variable (McSweeney *et al.* 2017). A lower tidal range translates to reduced tidal currents and velocities at the mouth which enables sediment stabilisation in the channel.

Tidal ranges, in combination with river runoff, are also good predictors of the expected salinity regime in an estuary as meso- and macrotidal estuaries are often marine-dominated during the low flow period as a result of high tidal flushing. While microtidal estuaries is more weakly flushed by the tide resulting in more brackish to even fresh conditions under even relative low flow conditions.

A.5.4.2 Estuarine Functional Typing

Drawing on the IUCN GET and South African approaches Table A.12 presents the proposed construct of functional typing of Southern African typology for estuarine ecosystems.

Table A.12 Proposed construct of Southern African typology for estuarine ecosystems

LEVEL 1: REALM	LEVEL 2: BIOME	LEVEL 3: FUNCTIONAL GROUP	LEVEL 6: FUNCTIONAL TYPE
Marine/Freshwater/ Terrestrial	MFT1 Brackish tidal systems	MFT 1.1 Coastal River Deltas	River Deltas
Freshwater/Marine	FM1 Transitional waters	FM 1.2 Permanently open riverine estuaries and bays	Permanently open
			Fluvially dominated
			Estuarine Bays
			Estuarine Lagoons
		FM 1.3 Intermittently closed coastal lagoons	Intermittently open/closed
			Estuarine lakes
Freshwater	F2 Lakes biome	F 2.1 Large permanent freshwater lakes	Freshwater Coastal Lakes

The estuarine functional types considered relevant to Southern African estuaries include:

- *River deltas* are formed by river-borne sediment that is deposited at the edge of a standing or slow-moving water body such as the ocean, but it can also be a lake, a reservoir, and rarely, another river (Seybold *et al.* 2007). In a delta, sediments accumulate seaward of the average shoreline, whereas, in an estuary, sediments accumulate within the river valley. River deltas are formed when the river inflow and associated sediment transport dominate and coastal processes, such as reworking by waves or tides, are relatively weak (Perillo 1995; Coleman and Wright 1975). The morphology and sedimentary processes of a delta depend on the river inflow regime, the sediment load of the river, and the relative magnitudes of tides, wave energy and ocean currents (Coleman and Wright 1975). The size, geometry and location of the receiving water body also affect the formation of a delta. Most often deltas form in areas with extensive coastal plains and low tidal regimes. As fluvial processes dominate in deltas, most develop extensive, meandering channel configurations that are highly dynamic, resulting in highly complex salinity regimes. During periods of high flow these systems tend to be highly turbid and muddy. Tidal ranges can vary from very similar to that of the sea to high constricted, depending on channel configuration and flow regime. However, most delta systems are relatively shallow as a result of the high sediment load in associated rivers. River Deltas are ecologically important since they generally support a high diversity of habitats (e.g. tidal flats, mangroves, saltmarsh, meandering channels, extensive floodplains) and associated species. Most river deltas are also associated with extensive offshore river plumes and fans, especially during the high flow season.
- *Permanently Open Estuaries* (also known as tidal river lagoons or Predominantly Open Estuaries) are open to the sea for more than 90% of the time (Whitfield 1992; Van Niekerk *et al.* 2020). Some are permanently open owing to perennial river flow or the presence of a large

tidal prism. Permanently Open estuaries are linear systems in which mixing processes are dominated by both fluvial inputs and tidal action creating vertical and horizontal salinity gradients. Under low river flows and high summer evaporation, hypersalinity can develop in the upper reaches. The degree to which the mouth is restricted depends on the rate and volume of freshwater inflow. Tidal amplitude ranges are similar to that observed in the ocean but can become highly restricted during periods of low flow. Systems subjected to high variance in seasonal inflows, can become severely constricted during the low flow period or droughts, decreasing the tidal amplitude, and increasing the duration of the ebb-tidal cycle. Regular flooding results in relatively mobile sediments. These estuaries usually support wetlands, salt marshes, macrophyte beds and marine and estuarine fauna (Whitfield 1992). Surprisingly, their size varies considerably ranging from very small (<10 ha) to very large (>7 500 ha), with smaller systems subjected to high tidal flows or afforded a degree of protection against direct wave action by rocky headlands or subtidal reefs, which assists in maintaining an open mouth.

- *Fluvially Dominated Estuaries* (also known as river mouths, river-dominated and tidal river mouths) are large, shallow, sediment-rich, freshwater-dominated systems fed by large catchments (Van Niekerk *et al.* 2020). These systems have very high sediment turnover, often develop ebb-tidal deltas, are turbid and can close during periods of low flow, e.g. uThukela and Orange estuaries. Fluvially Dominated estuaries tend to be constricted and can even periodically close during low flows. Fluvial processes are dominant, and salinities are mostly fresh throughout the estuary for more than half the time. During peak flood conditions, outflows can influence salinities for a considerable distance offshore. (In South Africa a smaller, fluvially dominated sub-type (<15 ha in size), was also identified that occur along rocky shores and are relative sediment-starved with unrestricted mouths. This subdivision will not be applied in the Southern African typology as a result of data limitations.)
- *Estuarine Bays* (also known as coastal or estuarine embayments) are permanently linked to the sea by unrestricted, deep mouths and are dominated by tidal processes, with tidal amplitude close to that of the sea (Whitfield 1992; Van Niekerk *et al.* 2020). These are large systems (>1200 ha) with typically round basins where only the upper reaches experience a degree of constriction to tidal flows. As a result of relatively low river inputs, they have a predominantly euryhaline salinity regime in the lower and mid reaches, with freshwater mixing processes being mostly confined to the more restricted upper areas. Sediments are typically marine in origin and grain size distributions are stable over time. There are few Estuarine Bays in Southern Africa.
- *Estuarine Lagoons* share many of the characteristics of estuaries (Van Niekerk *et al.* 2020), including calm waters protected from marine wave action and biota that reflect many of the species usually found in estuaries. However, this type of system lacks surface riverine inflow and a normal estuarine salinity gradient. Freshwater inputs to these systems are mostly provided in the form of groundwater but can be through ephemeral small rivers. Estuarine Lagoons represent a relative unique coastal ecosystem type and are recognised as an estuary type because their functioning relies on both freshwater and marine inputs into a semi-

enclosed embayment. Estuarine Lagoons are permanently connected to the sea and are therefore marine dominated. Tidal action is the dominant mixing process and sedimentary processes are thus generally stable. Tidal amplitude and water levels are close to those of the sea.

- *Intermittently Closed Estuaries (also called Temporarily open/closed)* are linear or funnel shaped, with highly restricted inlets. Water levels are dominated by the state of the mouth (Van Niekerk *et al.* 2020). Tidal ranges are very restricted, varying from 10-50 cm. Open phase mixing processes are dominated by fluvial input and partially by tides. The open phase is also associated with reduced, or even minimal, water column area. When closed, wind and seepage losses through the berm play a key role. Sediment composition is largely stable, resetting mainly during floods. Salinity regimes range from almost fresh to hypersaline, which in large systems can develop during times of low flow or droughts. Smaller systems tend to be 'perched' above normal tidal levels, resulting in little to no open water area during the open mouth low tide state. Small Intermittently Closed estuaries also tend to be fresher in character as they have less connectivity with the sea (Van Niekerk *et al.* 2020). Habitat diversity is often lower the smaller the estuary and thus overall species diversity and abundance are reduced. (In South Africa Intermittently Closed Estuaries were further divided into small and large categories using a total habitat area of 15 ha (associated with ~10 ha of open water area) as the dividing threshold. This subdivision will not be applied in the Southern African typology as a result of data limitations.)
- *Arid Predominantly Closed Estuaries* is a subtype *Intermitted Closed* subtype that was identified along the South African coastline, but only assigned to handful of estuaries (6) along this coastline. Efforts will be made to investigate if this type can be assigned to systems along the Namibian and Southern Angola coastline with relative confidence based on just visual imagery and available spatial information (e.g. FEOW). If not, this type will be collapsed into the larger *Intermitted Closed* category. Arid Predominantly Closed Estuaries are linear or funnel-shaped and closed on annual to decadal time scales (Van Niekerk *et al.* 2020). This type of estuary only occurs along Xeric coastlines. Salinities tend to be euryhaline to hypersaline as a result of low fluvial input and high evaporation rates. Thus, mixing processes tend to occur over long time periods and are dominated by the effects of evaporation, winds and seepage through the berm at the mouth. Occasional breaching and overwash during high sea conditions provide for marine input and connectivity. Sediment processes are generally stable on decadal time scales and are reset by large intermittent flash floods. Water levels are determined by the interplay between sand berm level, evaporation rates and seepage losses. Groundwater and inflows from local fountains replenish these losses and influence the salinity regimes of these estuaries. Arid conditions promote the growth of unique vegetation such as salt-tolerant, succulent species. Fish relies on 'suicidal' recruitment that is largely a function of connectivity with the sea and the degree of overwash during high seas. Safe return to the sea only occurs during floods and depends on a quick breach and fish not suffocating in sediment-laden water backing up against the berm. Invertebrate diversity, abundance and

community structure are related to changing salinity gradients, including long cycles of hypersalinity with a high biomass of brine shrimp *Artemia* sp. Cycles of *Artemia* abundance follow salinity regimes that in turn affect the diversity, abundance and occurrence of flamingos and other birds that feed on them.

- *Estuarine Lakes* (also known as Intermittently Closed and Open Lakes and Lagoons) comprise one or more large circular water bodies connected to the sea by a constricted inlet channel (Whitfield 1992; Van Niekerk *et al.* 2020). Freshwater input can be from a single or multiple large rivers, groundwater or aquifers, or multiple small waterways or streams feeding into the basin, or a combination thereof. Maximum water levels are determined by berm height, mouth state and freshwater input. Marine connectivity varies from almost permanently open (strongly connected) to intermittently closed on annual scales (weakly connected). Salinities are highly variable, ranging from fresh to hypersaline because of differing freshwater inputs (surface and ground water), evaporation and the extent and duration of the marine connection. Mixing processes are dominated by wind and, to a lesser extent fluvial inputs, owing to their restricted mouths and relatively large surface areas. Average tidal amplitudes are often negligible (10s cm) when connected to the sea, primarily due to restricted mouth conditions and the large attenuation area of the lakes. Sediment processes tend to be stable, with infilling occurring over long-time scales and system resetting confined to larger flood events.
- *Coastal Freshwater Lakes* are large permanent freshwater lakes (>100 km^2) that never connect to the ocean but may support remnant estuarine species (Kingsford *et al.* 2020). They are prominent landscape features that are connected to one, or more rivers, either terminally (stop at the lake) or as flow-through systems. High niche diversity and large volumes of permanent water (extensive, stable, connected habitat) support complex trophic webs with high diversity and abundance. Biota, such as aquatic macrophytes and macroinvertebrates and fish, often display high catchment-level endemism, in part due to long histories of environmental variability in isolation. Recruitment of many organisms is strongly influenced by physical processes such as large inflow events.

This study will not be classifying micro-systems (ephemeral outlets, micro-estuaries and waterfalls) in detail as field observations and/or high-resolution spatial data are not available to do so at the sub-continental-scale. Most smaller outlets will be grouped as *Ephemeral, i.e.* very small water bodies (<1 ha in area or <100 m in length) that are non-permanent (i.e. they can dry out during periods of low flow) or are elevated above mean sea level with a perched outflow channel that does not facilitate tidal mixing of salt- and freshwater (Dalu *et al.* 2018; Human *et al.* 2018). They act as a limited conduit between the land and the sea during periods of elevated stream outflow or exceptionally high storm sea events. *Coastal waterfalls* are water bodies elevated more than 10 m above mean sea level that have no direct channel connection with the sea. Due to their elevation, they do not serve as conduits between the land and the sea. These systems occur along rocky shorelines where the presence of bed rock does not allow for channel erosion to mean sea level. However, the continuous outflow of freshwater into rocky coastal habitats may support unique marine biotic assemblages along the coast.

The key features to consider in the identification of estuarine functional types that can be verified from spatial data are summarised in Table A.13.

Table A.13 Key physical features considered in identification of estuary functional types.

FUNCTIONAL TYPE	KEY PHYSICAL FEATURES
River Deltas	• Permanently open mouth • Associated with tropical biogeographical regions • The major river system of a high Strahler River Order (6-9) • Nearshore depositional area • One main river divides into multiple sub-channels as it reaches the coastal plain • A high number of meandering/braided channels and a high variance in channel location and size • High sediment load and turbidity are visible in most imagery • Extensive mud flats (visible as red or orange substrate) • Presence of fluvial turbidity plume visible offshore • Mangroves are likely to be present along tropical, subtropical and possibly warm temperate coastlines
Permanently open	• Permanently open mouth, but the mouth can become very constricted at times • Open mouth conditions are associated with large rivers (i.e. Strahler River Order 6-9) • Open mouth conditions along micro- and mesotidal coast are associated with high river inflow (e.g. Strahler River Order ≥4) • Along macrotidal coast tidal flows can maintain open mouth conditions at even relative low river inflow conditions (e.g. Strahler River Orders 1-4) • Single confined channel (or a small number of old channels) flowing into the ocean • Stable channel configuration between imagery • Relative clear water column throughout most of the year • Can be deep or shallow • Mangroves are likely to be present along tropical, subtropical and possibly warm temperate coastlines
Fluvially dominated	• Permanently open mouth, but the mouth can become very constricted or even close for a small (<10%) percentage of the time • Generally associated with a large river of a high Strahler River Order (6-9) • Single confined channel (or a small number of old channels) flowing into the ocean • Highly dynamic, meandering/braided channels • Highly turbid water column • Turbidity plume visible in the nearshore during high flow or seasonally • Mangroves are likely to be present along tropical, subtropical and possibly warm temperate coastlines
Estuarine Bays	• Large water body • Wide open, unrestricted entrance to the sea resulting in an unrestricted tidal exchange • Small to medium size rivers flowing in the bay area. • Potentially a deep system (i.e. can't see the bottom as indicated by dark blue cloud) • If time series available, limited imagery showing some freshwater input (i.e. limited turbidity observed/turbidity not throughout the year or bay system) • The possible presence of muddy substrate

FUNCTIONAL TYPE	KEY PHYSICAL FEATURES
	• Mangroves are likely to be present along tropical, subtropical and possibly warm temperate coastlines.
Estuarine Lagoons	• Large partially enclosed water body • Constraint entrance possibly resulting in tidal restrictions • Ephemeral streams (e.g. Strahler River Order 1 or 2) flowing in the lagoon area • Shallow bottom (can see bottom and channel in parts of the system) • White sandy substrate/sand flats (presence of muds indicative of river inputs and more likely to be Estuarine Bay) • No evidence of freshwater input (no turbidity noted in imagery) • Mangroves are likely to be present along tropical, subtropical and possibly warm temperate coastlines, but given the absence of sediment supply this may not be defining feature
Estuarine lakes	• Large permanent water body • One or more round-shaped water bodies with connecting channels • Connected to the sea (either permanently or periodically) with a small mouth • One or more rivers feeding into lake system. • A complex configuration that can be a mix of estuarine and river types • Can be groundwater-fed with poorly developed flow lines (check literature) • Mangroves are not likely to occur given the restricted tidal ranges or close conditions (inundated during closed periods)
Freshwater Coastal Lakes	• Large permanent water body • One or more round-shaped water bodies with connecting channels • No connection to the sea • One or more rivers feeding into lake system • Mangroves are not likely to occur (no tidal exchange)
Intermittently open/closed	• Small to medium size permanently water body • Mouth closes intermitted or nearly permanently to the sea • Likely to occur along Microtidal coast but can occur along Mesotidal coast. Very unlikely to occur along Macrotidal coast. • Highly likely to occur in Xeric freshwater regions where river inflow is low and highly variable, unlikely to occur in tropical regions where freshwater inputs are more stable • Mangroves are not likely to occur (inundated during closed periods)
Ephemeral outlet/ Coastal seep	• Ephemeral water body • Highly likely to occur in Xeric freshwater regions • Associated with low Strahler River Order 1 or 2 along tropical and subtropical coasts, but can be associated higher river orders (1-4) along temperate Xeric regions • Mangroves are not likely to occur (no tidal exchange)

A.5.5. Construct of Estuarine Ecosystem Typology Framework

The framework entails the combination of the three main elements of the classification into a descriptive first-level Estuarine Ecosystem Typology for Southern Africa (Figure A.19), that is:

- Biogeographical regions (4 regions)
- Tidal ranges (3 classes)
- Functional type (8 types).

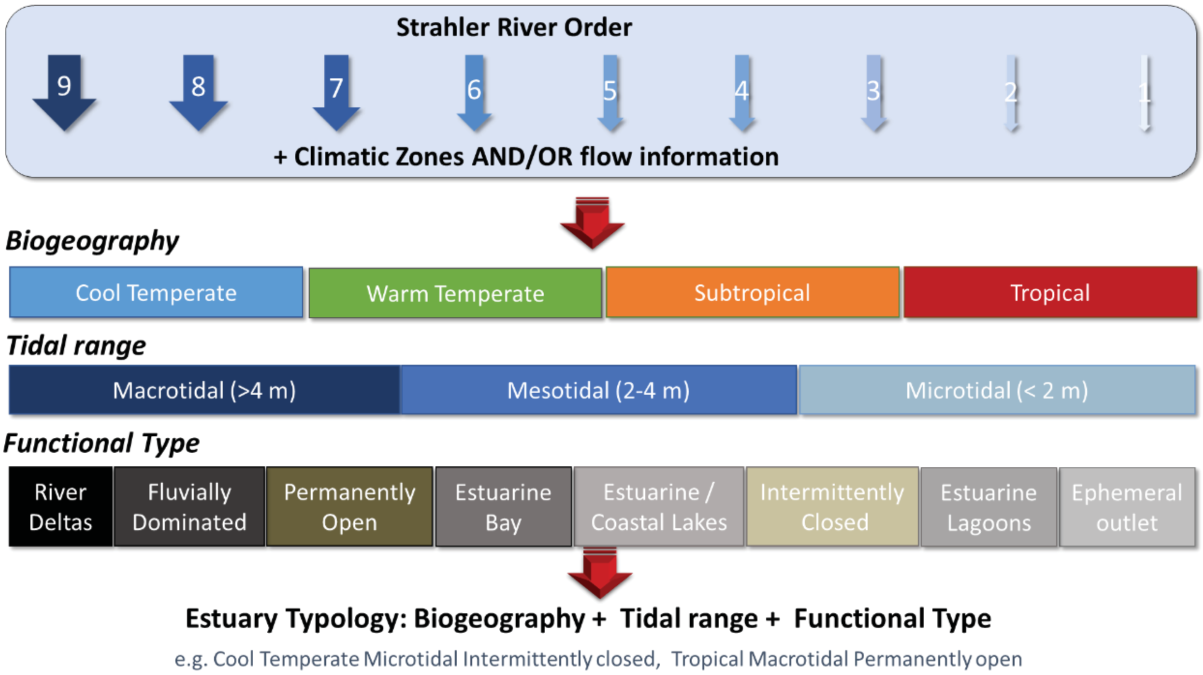


Figure A.19 Development of a first level Estuarine Ecosystem Typology for Southern Africa

This yields 96 possible estuarine ecosystem types for the region, but not all functional types occur in all biogeographical regions (e.g. River Deltas seldom occur in the drier cool temperate regions of the world) or under all tidal regimes (e.g. Intermitted Closed Estuaries seldom occur on macrotidal coasts).

The combination of biogeographical regions (broad predictor of runoff regime and biotic composition) and tidal regime (mouth state and salinity regime) provides for a relative descriptive classification that can be used for predicting typical abiotic conditions expected to occur in an estuary, as well as the broad biotic communities that should be associated with it. In the absence of detailed field observations, such a classification can be used for E-Flows and biodiversity assessments.

A.6. Provisional Ecosystem Typing of Southern African Estuaries

Of the regions 2 500 outlets to the sea, those associated with Strahler River Orders 6 to 9 have already been provisionally identified based on the combination of biogeographical regions, tidal ranges, and functional types, although these will need to be verified with country-level specialists (Table A.14).

Table A.14 Provisional estuarine ecosystem type for Southern Africa, as well as distribution of major estuaries (linked Strahler River Orders 4 to 9)

BIOGEOGRAPHICAL REGION	TIDAL RANGE	FUNCTIONAL TYPE	NO. OF MAJOR ESTUARINE SYSTEMS

			(inked to Strahler River Orders 6 to 9)
Cool Temperate	Micro	Ephemeral	1
		Fluvially dominated	1
		Permanently open	1
Warm Temperate	Meso	Permanently open	1
	Micro	Fluvially dominated	1
		Intermitted open/closed	1
		Permanently open	2
Subtropical	Micro	Fluvially dominated	2
		Permanently open	3
Tropical	Macro	Estuarine Bay	1
		Permanently open	4
		Permanently open/Estuarine Lake	1
		River Delta	2
		Estuarine Bay	1
	Meso	Estuarine Bay	1
		Fluvially dominated	1
		Permanently open	10
		River Delta	4
		Estuarine Bay	1
	Micro	Estuarine Bay	1
		Permanently open	6
		Permanently open/Estuarine Lake	1
		River Delta	1

Details on the specific estuarine systems within each of these categories (focusing on major systems linked to Strahler River Orders 6 and 9) are presented below in Table A.15.

Table A.15 Estuary Ecosystem Typology for the major rivers (linked Strahler River Orders 6 to 9) linked to of Southern Africa

ID	RIVER ORDER	NAME	LATITUDE DD	LONGITUDE DD	BIOGEOGRAPHICAL REGION	TIDAL RANGE	FUNCTIONAL TYPE	COUNTRY	FEOW
24	7	Kouilou-Niari	-4.478	11.709	Tropical	Microtidal	Permanently open	Republic of Congo	532
48	9	Congo	-6.070	12.463	Tropical	Microtidal	River Delta	Angola	550
75	6	Mbridge	-7.203	12.850	Tropical	Microtidal	Permanently open	Angola	551
120	7	Cuanza	-9.343	13.148	Tropical	Microtidal	Permanently open	Angola	551
131	6	Longa	-10.239	13.492	Subtropical	Microtidal	Permanently open	Angola	551
140	6	Kuvo	-10.865	13.800	Subtropical	Microtidal	Permanently open	Angola	551
162	6	Catumbela	-12.434	13.487	Subtropical	Microtidal	Permanently open	Angola	551
251	6	Curoca	-15.721	11.913	Warm temperate	Microtidal	Intermitted open/closed	Angola	552
277	7	Cunene	-17.243	11.750	Warm temperate	Microtidal	Permanently open	Angola/ Namibia	552
398	6	Swakopmund	-22.691	14.521	Cool temperate	Microtidal	Ephemeral	Namibia	552
516	9	Orange (Gariep)	-28.634	16.450	Cool temperate	Microtidal	Fluvially dominated	Namibia/ South Africa	572
577	6	Olifants	-31.690	18.179	Cool temperate	Microtidal	Permanently open	South Africa	578
678	6	Gouritz	-34.346	21.886	Warm temperate	Mesotidal	Permanently open	South Africa	578
722	6	Gamtoos	-33.973	25.033	Warm temperate	Microtidal	Permanently open	South Africa	578
786	6	Great Kei	-32.682	28.386	Warm temperate	Microtidal	Fluvially dominated	South Africa	575
825	6	Mzimvubu	-31.627	29.550	Subtropical	Microtidal	Fluvially dominated	South Africa	575
903	6	Thukela	-29.229	31.501	Subtropical	Microtidal	Fluvially dominated	South Africa	576
942	6	Incomati	-25.777	32.741	Tropical	Mesotidal	Estuarine Bay	Mozambique	576
946	7	Limpopo	-25.208	33.510	Tropical	Mesotidal	Permanently open	Mozambique	576
1000	7	Save/Sabi	-20.908	35.072	Tropical	Mesotidal	Permanently open	Mozambique	576
1009	6	Mureia/Gorongosa	-20.518	34.688	Tropical	Macrotidal	Permanently open	Mozambique	576
1019	6	Buzi	-19.884	34.754	Tropical	Macrotidal	Permanently open	Mozambique	576
1022	6	Pungwe	-19.673	34.663	Tropical	Macrotidal	Permanently open	Mozambique	576
1062	8	Zambezi	-18.804	36.259	Tropical	Mesotidal	River Delta	Mozambique	561
1079	6	Cuacua	-17.934	36.900	Tropical	Mesotidal	Permanently open	Mozambique	564
1089	6	Licungo	-17.669	37.358	Tropical	Mesotidal	Permanently open	Mozambique	564
1093	6	Raranga	-17.467	37.704	Tropical	Mesotidal	Permanently open	Mozambique	564
1200	6	Lurio	-13.516	40.525	Tropical	Mesotidal	Permanently open	Mozambique	564
1266	7	Ruvuma	-10.500	40.419	Tropical	Mesotidal	Permanently open	Tanzania	564
1327	8	Rufiji	-7.767	39.359	Tropical	Macrotidal	River Delta	Tanzania	564
1365	6	Wani	-6.154	38.849	Tropical	Macrotidal	Permanently open	Tanzania	564
1443	6	Galana	-3.170	40.145	Tropical	Mesotidal	Permanently open	Kenya	567
1453	6	Tana	-2.531	40.519	Tropical	Mesotidal	Permanently open	Kenya	567
1781	6	Antainambalana	-15.450	49.741	Tropical	Microtidal	Estuarine Bay	Madagascar	583
1847	6	Maningory	-17.213	49.463	Tropical	Microtidal	Permanently open	Madagascar	583
1888	6	Vohitra	-18.975	49.104	Tropical	Microtidal	Permanently open/Estuarine Lake	Madagascar	583
1912	6	Mangoro	-19.993	48.788	Tropical	Microtidal	Permanently open	Madagascar	583
1968	6	Maroangaty	-23.352	47.701	Tropical	Microtidal	Permanently open	Madagascar	583
2073	6	Onilahy	-23.568	43.771	Tropical	Mesotidal	Fluvially dominated	Madagascar	582
2113	6	Mangoky	-21.446	43.467	Tropical	Mesotidal	River Delta	Madagascar	579
2154	7	Tsiribihina	-19.638	44.411	Tropical	Mesotidal	River Delta	Madagascar	579
2163	6	Menabe	-19.311	44.355	Tropical	Mesotidal	River Delta	Madagascar	579
2250	6	Mahavavy	-15.796	45.786	Tropical	Mesotidal	Permanently open	Madagascar	580
2273	7	Betsiboka	-15.971	46.463	Tropical	Macrotidal	River Delta	Madagascar	580
2311	7	Mahajambe	-15.429	47.171	Tropical	Macrotidal	Estuarine Bay	Madagascar	580
2357	6	Panantsova	-14.604	47.766	Tropical	Macrotidal	Permanently open/Estuarine Lake	Madagascar	580

APPENDIX B. A COMPARATIVE REVIEW OF DECISION SUPPORT TOOLS ROUTINELY USED BY SELECTED TRANSBOUNDARY RIVER BASIN ORGANISATIONS

Task 1 was done in conjunction with a European Union (EU)-supported project on the Okavango River. It was a desktop review that provided a broad comparative analysis of the suite of DS tools adopted by five intergovernmental River Basin Organisations (RBOs) that manage shared water resources: the Permanent Okavango River Basin Water Commission; the Orange-Senqu River Commission; the Nile Basin Initiative; the Zambezi Watercourse Commission, and the Mekong River Commission. The modelling tools documented by the RBOs were reviewed against the sort of information needed to evaluate whether development and management proposals were in line with social and environmental provisions in the RBOs' Vision Statements. A review of the model development timeline showed that prior to 2000 little capacity in modelling of hydrological, ecosystem, and social components of the river existed, but that these gaps have been addressed in recent years.

The review was published in an African Journal of Aquatic Science (AJAS) Special Medal Issue on Perspectives on Protecting African Freshwater Ecosystems in the Anthropocene (King and Palmer 2022). Guest Editors: Prof. Tally Palmer and Prof. Jackie King:

> BUKHARI H and BROWN C (2022) A comparative review of decision support tools routinely used by selected transboundary River Basin Organisations. *African Journal of Aquatic Sciences* **47** (3) 318-337. DOI: 10.2989/16085914.2021.1976610.

Abstract:

As human pressures on water resources increase, the data and decision support (DS) tools used in the governance, development and management of transboundary rivers are likely to become increasingly important. There are no universal, standardised selection processes or designs for these tools, and so it is up to individual River Basin Organisations (RBOs) to decide what to include in their capacities. this desktop study provides a broad comparative analysis of the suites of DS numerical modelling tools developed and utilised by five intergovernmental transboundary RBOs that advise their member states in the management of their shared water resources: the Permanent Okavango River Basin Water Commission; the Orange-Senqu River Commission; the Nile Basin Initiative; the Zambezi Watercourse Commission; and the Mekong River Commission. These DS tools were reviewed against the information required to enable the kinds of comprehensive assessments of proposed basin management and development plans defined in their respective agreements, which include not only hydrological parameters, but also environmental and social considerations. A review of the model development timelines showed that prior to 2000, little capacity existed in modelling of hydrological, ecosystem, and social components of the river, but that these gaps have been addressed in recent years.

APPENDIX C. THE USE OF ECOSYSTEM-BASED EFLOWS ASSESSMENT OUTPUTS FOR GLOBAL AND NATIONAL REPORTING PROCESSES

This appendix provides guidance on the use of EFlows assessments and EFlows-related outputs for rivers, wetlands and estuaries in global and national reporting processes, and as a framework for evaluating progress with the SDGs.

C.1. The use of EFlows outputs in global and national reporting processes

There are a wide variety of country-level reporting processes embedded in the international agreements, directives and conventions to which the majority of SADC countries are signatories, such as:

- Africa Agenda 2063 (https://au.int/en/agenda2063/overview)
- 2030 Kunming-Montreal Global Biodiversity Framework (GBF) (https://www.cbd.int/gbf/)
- The 2030 Agenda for Sustainable Development and Sustainable Development Goals as indicators (https://sustainabledevelopment.un.org/post2015/transformingourworld)
- Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar) (https://www.ramsar.org/)
- International Convention on Biological Diversity (CBD) (https://www.cbd.int/)
- IUCN Red Listing of Ecosystems (https://iucnrle.org/)
- United Nations Framework Convention on Climate Change (1992) and the Paris Agreement (https://unfccc.int/)
- Global Environment Outlook (GEO) (https://www.unep.org/global-environment-outlook)
- United Nations (UN) System of Environmental-Economic Accounting (SEEA) (https://seea.un.org/)
- Nairobi and Abidjan Conventions.

EFlows assessments conducted in a country, even at a desktop/screening level, can provide invaluable data and information that can be aggregated to provide country-level and used to measure and report on progress in achieving international obligations or targets.

The relevance of the outputs from EFlows assessments for the various global and national reporting processes and the indicator/s to be addressed are outlined in Table C.5 to Table C.20. The EFlows components that are considered in each table are:

Ecosystem typology:	Grouping of key abiotic and biotic aspects into indicators with similar flow sensitivity and responses to changes in flows.
Resource delineation:	Maps of the extent of an aquatic ecosystem, and delineation into ecologically similar reaches or zones

Model of ecosystem function: Conceptual or numerical model(s) constructed of ecosystem function and responses to flow changes and other pressures

Pressures: Assessment of the baseline types and degrees of pressures an (e.g. flow modification, pollution, land-use change and development, exploitation of living resources, biological invasions)

Baseline Ecological State/Condition: The baseline condition or health of an aquatic ecosystem relative to a benchmark; usually natural

Target State/Condition: The management targeted condition or health of an aquatic ecosystem relative to a benchmark; usually natural

EFlows requirements: The timing and volume of water flows allocated to maintain the Target State

Water quality requirements: The water quality allocated to maintain the Target State

Biotic requirements: Biotic requirements (for habitats, invertebrates, fish, birds, mammals or reptiles) to meet Target State of the resource

Ecosystem services: Ecosystem services (e.g. fishing, recreational water quality) to be provided by the resource under the Target State.

C.1.1. Africa Agenda 2063

Africa Agenda 2063 is a strategic framework for the socioeconomic transformation of the African continent over a 50-year period, from 2013 to 2063. It was put forward by African heads of state and government at the Golden Jubilee celebrations of the formation of the Organisation of African Unity/African Union in 2013. It aims to serve as a roadmap for Africa's development aspirations, guiding policy formulation and implementation at the continental, regional, and national levels to realize the vision of "The Africa We Want." Key themes and goals are related to economic growth and prosperity, infrastructure development, human capital investment, peace and security, cultural preservation, environmental sustainability, Pan-Africanism, and global partnerships. The Africa Agenda 2063 builds on the pledges made through the 50th Anniversary Solemn Declaration.

Although overall prosperity of people and sustainable development of the continent indirectly relate to the informed management of resources, several of the aspirations put forth in the Africa Agenda 2063 relate directly to aquatic ecosystems (Table C.1).

Table C.1 Summary of the relationship between Africa Agenda 2063 environmental and sustainability related goals and EFlows outputs

AFRICA AGENDA 2063

Several of the aspirations put forth in the Africa Agenda 2063 relate directly to aquatic ecosystems, such as:

- We aspire that by 2063, Africa shall be a prosperous continent, with the means and resources to drive its own development, with sustainable and long-term stewardship of its resources and where Africa's unique natural endowments, its environment, and ecosystems, including its wildlife and wild lands are healthy, valued and protected, with climate resilient economies and communities.
- Africa's Blue/ocean economy, which is three times the size of its landmass, shall be a major contributor to continental transformation and growth, through knowledge on marine and aquatic biotechnology, the growth of an Africa-wide shipping industry, the development of sea, river and lake transport and fishing; and exploitation and beneficiation of deep-sea mineral and other resources
- Africa shall have equitable and sustainable use and management of water resources for socio-economic development, regional cooperation and the environment.

Further, its call to action also provides specific actions related to water resources:

- Implementing joint cross-border investments to exploit shared natural resources.
- Developing strategies to grow the African Blue/ocean and green economies.
- Act with a sense of urgency on climate change and the environment, implementation of the Programme on Climate Action in Africa including sustainable exploitation and management of Africa's diversity for the benefit of its people.

The 42,000 MW Grand Inga Dam project is identified by the Africa Agenda as a flagship project key to accelerating Africa's economic growth.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

C.1.2. 2030 Kunming-Montreal Global Biodiversity Framework (GBF)

The 2030 Global Biodiversity Framework (GBF) was signed by 196 nations on 19 December 2022 to "take urgent action to halt and reverse biodiversity loss" by 2030. The GBF consists of four overarching global goals to protect nature, including: halting human-induced extinction of threatened species;

sustainable use and management of biodiversity; fair sharing of the benefits from the utilization of genetic resources; and that adequate means of implementing the GBF be accessible to all Parties.

The GBF is more inclusive, more comprehensive, more SMART (specific, measurable, achievable, relevant, and time-bound), and more complex than the Aichi Biodiversity Targets that preceded it. Two out of eight targets that aim to reduce threats to biodiversity (Targets 1 to 8), shows increased ambition compared to the Aichi Targets: to effectively conserve 30% of terrestrial, inland water, coastal, and marine areas (compared to 17% for terrestrial and inland water, and 10% for coastal and marine areas by 2020); and to ensure that at least 30% of degraded terrestrial, inland water, coastal, and marine ecosystems are under effective restoration by 2030 (compared to 15% by 2020). Targets 9 to 13 aim to meet people's needs through sustainable use and benefit-sharing, with Target 12 aiming for "improved connectivity of biodiversity through green and blue spaces in urban areas, something that was not included in the Aichi Targets," according to the ENB. Targets 14 to 23 cover the tools and solutions for implementation and mainstreaming, including quantified targets for resource mobilization. While Target 19 aims to substantially and progressively increase the level of financial resources from all sources to at least USD 200 billion per year by 2030, including by increasing transfer from developed to developing countries to at least USD 20 billion per year by 2025, and at least USD 30 billion per year by 2030.

The key GBF targets relevant to rivers, wetlands and estuaries include:

- TARGET 2: Restoration of 30% of terrestrial, inland waters and marine ecosystems (Table C.2)
- TARGET 3: Effective conservation and management of at least 30% of the world's land, inland waters, coastal areas and oceans (Table C.3)
- TARGET 8: Climate change mitigation and adaptation including a focus on Blue and Teal Carbon (Table C.4)
- TARGET 11: Restore, maintain and enhance nature's contributions to people, including ecosystem functions and services (Table C.5).

Table C.2 Summary of the relationship between GBF Target 2 indicator and EFlows outputs

TARGET 2: 30% OF AREAS OF DEGRADED TERRESTRIAL, INLAND WATER, AND COASTAL AND MARINE ECOSYSTEMS ARE UNDER EFFECTIVE RESTORATION
Ensure that by 2030 ≥30% of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity
REQUIREMENTS
Habitat degradation is the result of human-induced processes that result in a decline in biodiversity, ecosystem functions and services, and resilience and can occur in terrestrial, freshwater or marine and coastal ecosystems. This target aims to ensure that 30% of the total area of degraded terrestrial, inland water and marine and coastal ecosystems are under effective restoration by 2030. Restoration refers to the process of actively managing the recovery of an ecosystem that has been degraded, damaged or destroyed. Restoration activities can be undertaken for a variety of reasons and across a continuum of actions. For example, ecological restoration includes efforts to increase the area of a natural ecosystem and its integrity through

recovering an ecosystem that has been degraded or destroyed, this includes conversion of non-natural transformed ecosystems back to a natural condition. Ecosystem rehabilitation includes efforts to increase ecosystem functions and services of transformed ecosystems. Given, the continuum of restoration activities, efforts to reach this target should be specific and identify the type of restoration being undertaken, the overall objectives being sought and the type of area or ecosystem being restored.

- Headline indicators: Area under restoration
- Component indicators: Extent of natural ecosystems by type, Maintenance and restoration of connectivity of natural ecosystems
- Relevant Complementary indicators: Habitat distributional range, Global Ecosystem Restoration Index, Free-flowing rivers, Status of Key Biodiversity Areas Biodiversity Habitat Index , Red List Index, Red List of Ecosystems.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services			

Table C.3 Summary of the relationship between the GBF Target 3 indicator and EFlows outputs

TARGET 3: 30% OF AREAS OF TERRESTRIAL AND INLAND WATER AREAS, AND OF MARINE AND COASTAL AREAS ARE EFFECTIVELY CONSERVED AND MANAGED

Ensure and enable that by 2030 ≥30% of inland water areas, and marine and coastal areas, especially those with important biodiversity and ecosystem functions and services, are conserved and managed through ecologically representative, well-connected and equitably-governed systems of protected areas and other area-based conservation measures, recognizing indigenous and traditional territories, where applicable, and integrated into wider landscapes, seascapes and the ocean, while ensuring that any sustainable use, where appropriate in such areas, is fully consistent with conservation outcomes, recognizing and respecting the rights of indigenous peoples and local communities, including over their traditional territories.

REQUIREMENTS

Well-governed, effectively managed and representative protected areas and other effective area-based conservation measures (OECMs) safeguard both habitats and populations of species and deliver important ecosystem services and benefits to people. They are central to biodiversity conservation at local, national and global levels. Protected areas and OECMs range from strictly protected areas to areas that allow sustainable use consistent with the protection of species, habitats and ecosystem processes.

- Headline indicators: Coverage of protected areas and OECMs

- Component indicators: Protected area coverage of key biodiversity areas, Protected Area Management Effectiveness (PAME), The number of protected areas that have completed a site-level assessment of governance and equity (SAGE), Species Protection Index
- Relevant Complementary indicators: Protected area downgrading, downsizing and degazettement, Status of key biodiversity areas, IUCN Green List of Protected and Conserved Areas, Number of hectares of UNESCO designated sites, Protected area and OECM management effectiveness indicator, Extent to which protected areas and OECMs cover Key Biodiversity Areas important for migratory species, Coverage of Protected areas and OECMS and traditional territories, Ramsar Management Effectiveness Tracking Tool (RMETT), Percentage of biosphere reserves that have a positive conservation outcome and effective management, Extent of indigenous peoples and local communities' lands that have some form of recognition, Species Protection Index, Red List of Ecosystems, Proportion of terrestrial, freshwater and marine ecological regions which are conserved by protected areas or other effective area-based conservation measures.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services			

Table C.4 Summary of the relationship between the GBF Target 8 indicator and EFlows outputs

TARGET 8: MINIMIZE THE IMPACT OF CLIMATE CHANGE AND OCEAN ACIDIFICATION ON BIODIVERSITY

Minimize the impact of climate change and ocean acidification on biodiversity and increase its resilience through mitigation, adaptation and disaster risk reduction actions, including through nature-based solutions and/or ecosystem-based approaches, while minimizing negative and fostering positive impacts of climate biodiversity.

REQUIREMENTS

Climate change is one of the main direct drivers of biodiversity loss. In addition to climate change, rising atmospheric carbon dioxide concentrations have also resulted in ocean acidification. Various mitigation, adaptation and disaster risk reduction measures, including nature-based solutions and/or ecosystem-based approaches, have the potential to increase the resilience of ecosystems and human livelihoods to the impacts of climate change, including reducing emissions from deforestation and other land-use changes, and by enhancing carbon sinks. These approaches can also deliver numerous social, economic and environmental co-benefits. This target focuses on (a) minimizing the impacts of climate change and ocean acidification on biodiversity, (b) the contribution of biodiversity, through nature-based solutions or ecosystem-based approaches, to climate mitigation and adaptation and disaster risk reduction and (c) minimizing negative and fostering positive impacts of climate action on biodiversity.

- Component indicators: Total climate regulation services provided by ecosystems by ecosystem type (System of Environmental Economic Accounts), Number of countries that adopt and implement national disaster risk reduction strategies that include biodiversity, National greenhouse inventories from land use and land use change Bioclimatic Ecosystem Resilience Index (BERI)
- Relevant Complementary indicators: Above-ground biomass stock in forests (e.g. mangroves) (tonnes/ha), National greenhouse inventories from land use and land use change, Proportion of local governments that adopt and implement local disaster risk reduction strategies, Number of least developed countries and small island developing States with nationally determined contributions, long-term strategies, national adaptation plans, Index of coastal eutrophication, Carbon stocks and annual net Greenhouse gas (GHG) emissions.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services			

Table C.5 Summary of the relationship between the GBF Target 11 indicator and EFlows outputs

TARGET 11: RESTORE, MAINTAIN AND ENHANCE NATURE’S CONTRIBUTIONS TO PEOPLE, INCLUDING ECOSYSTEM FUNCTIONS AND SERVICES

Restore, maintain and enhance nature’s contributions to people, including ecosystem functions and services, such as the regulation of air, water and climate, soil health, pollination and reduction of disease risk, as well as protection from natural hazards and disasters, through nature-based solutions and/or ecosystem-based approaches for the benefit of all people and nature.

REQUIREMENTS

Nature’s contributions to people, a concept similar to and inclusive of ecosystem services, refer to all the contributions from biodiversity to people’s well-being. These contributions include material contributions, regulating services and other non-material contributions, such as spiritually and culturally. As a result of the ongoing decline of biodiversity, nature’s contributions to people are in decline, with serious implications for human well-being and social cohesion. The restoration, maintenance and enhancement of nature’s provides an important rational for the conservation and sustainable use of biodiversity. This target calls for the range of nature’s contributions to people to be restored, maintained or enhanced by 2030 and places specific emphasis on the regulation of air, water and climate, soil health, pollination and reduction of disease risk, as well as protection from natural hazards and disasters. To accomplish this the target specifies nature-based solutions and/or ecosystem-based approaches. Nature-based solutions here refer to actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits.

- Headline indicators: Services provided by ecosystems
- Component indicators: Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population, Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services, Proportion of bodies of water with good ambient water quality, Level of water stress
- Relevant Complementary indicators: Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management, Proportion of population using safely managed drinking water services, Mortality rate attributed to household and ambient air pollution (SDG indicator 3.9.1).

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements			
Ecosystem services	●	●	●

C.1.3. 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs)

The 2030 Agenda for Sustainable Development, adopted by all UN Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future (https://sustainabledevelopment.un.org/post2015/transformingourworld). This Agenda builds on the previous targets of the UN through the Aichi Targets (2011-2020). At its heart are the 17 SDGs, also known as the Global Goals, which are an urgent call for action by all countries – developed and developing – in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and aquatic biodiversity (Table C.6 to Table C.9).

The SDGs use main and sub-indicators to measure the set ideals of equal and sustainable development between countries. Four of the 17 SDGs have direct links to the geographic extent, pressures, and present or desired ecological condition of aquatic ecosystems, including:

  - GOAL 6: Clean Water and Sanitation
  - GOAL 13: Climate Action
  - GOAL 14: Life Below Water
  - GOAL 15: Life on Land.

Table C.6 Summary of the relationship between the SDG 6 indicator and EFlows outputs

GOAL 6: Ensure availability and sustainability and sustainable management of water and sanitation for all

Access to drinking water and sanitation is a human right and, together with water resources, a key determinant in all aspects of social, economic and environmental development. Besides access to drinking water, sanitation and hygiene, Goal 6 also comprises targets such as protecting and restoring water-related ecosystems (including mountains, forests, wetlands, rivers and lakes). Goal 6 aims to improve water quality and reduce water pollution, especially the type caused by hazardous chemicals. It also advocates cross-border cooperation as the key to managing water resources in an integrated fashion at all levels.

SDG Indicator 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally

Measured/modelled water quality conditions can be used to report on the proportion of bodies of aquatic ecosystems with good ambient water quality as well as key pollution pressures/sources on these ecosystems. For example, in South Africa regional-scale water resource status information was combined with monitoring information to report on indicator 6.3.2.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition			
Flow requirements			
Water quality requirements	●	●	●
Biotic requirements			
Ecosystem services			

SDG Indicator 6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate

Aggregating regional-scale results of EFlows assessment would allow for reporting on indicator 6.5.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			

Pressures			
Baseline Ecological State/Condition			
Target State/Condition			
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements			
Ecosystem services			

SDG Indicator 6.6: By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes

Measured/modelled condition can be used to report on the change in the extent of aquatic ecosystems over time (with a focus on the extent and water quantity). For this, the type of ecosystems, their extent, how they function, the pressures on them, and their condition is needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750 before large-scale human interventions). EFlows information on flow, water quality, biota and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

Table C.7 Summary of SDG 13 reporting requirements to EFlows outputs

GOAL 13: Take urgent action to combat climate change and its impacts

Climate change is a key sustainable development challenge. The warming of the earth's atmosphere is triggering changes in the global climate system that threatens the livelihoods of large sections of the population in less developed countries. Furthermore, changes in precipitation and temperature cycles are also affecting ecosystems such as wetlands and oceans, as well as the plants, animals and people that live in them. Goal 13 calls on countries to incorporate climate protection measures in their national policies and assist each other in responding to the challenges at hand. Goal 13 advocates strengthening resilience to climate-related natural disasters and reaffirms the commitment undertaken by developed countries to mobilise funds to help developing countries adapt to climate change.

SDG Indicator 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries

Key to ensuring Goal 13.1 is the regional scale Climate Change Vulnerability assessment of freshwater resources (rivers, wetland and estuaries) to using existing EFlows technologies to assess the venerability to climate change and the projected direction of change under present levels of catchment development.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

SDG Indicator 13.2: Integrate climate change measures into national policies, strategies and planning

The determination and implementation of EFlows requirements are critical in ensuring health and productivity in the face of change in the hydrological processes. Environmental flow requirement studies should therefore include projected “Climate Change operational scenarios” to determine future catchment yields and ecological requirements. The duration and extent of future droughts needs to be explicitly evaluated and planned for in arid countries such as South Africa. Catchment connectivity is critical to ensuring adaptation to future climate shifts.

A key indicator would be the number of EFlows assessments in a region that included climate change scenarios.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures			
Baseline Ecological State/Condition			
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

Table C.8 Summary of SDG 14 reporting requirements to EFlows outputs

GOAL 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Pollution and over-exploitation of our oceans are posing ever-greater problems, such as an acute threat to biodiversity, ocean acidification and an increase in plastic waste. Besides industrial fishing and the commercial use of marine resources, climate change is placing marine ecosystems under increased pressure. A continuously growing global population will be even more dependent on marine resources in future.

Goal 14 advocates significantly reducing all kinds of marine pollution and minimising ocean acidification by 2025, as well as sustainably managing and protecting marine and coastal ecosystems by as early as 2020. It also aims, by 2020, to regulate harvesting in an effective manner and to halt overfishing by ending illegal and unregulated fishing and destructive fishing practices.

SDG Indicator 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution

Measured/modelled water quality conditions of coastal rivers and estuaries can be used to report on the proportion of bodies of aquatic ecosystems with good ambient water quality as well as key pollution pressures/sources on these ecosystems.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

SDG Indicator 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans

EFlows information on desired state for coastal rivers, wetlands and estuaries and associated habitats, biota flow, and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures			

Baseline Ecological State/Condition			
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

SDG Indicator 14.3: Minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels

Estuarine and coastal pH levels are strongly dependent on coastal upwelling; catchment geology and land-use; freshwater inflow; nutrient input; primary production and decomposition (Feely *et al.* 2010; Laurent *et al.* 2017). Changes in land-use can result in changes in freshwater alkalinity and CO_2 fluxes up to 0.5 units. The pH in estuarine habitats (e.g. mangroves, salt marshes and macroalgal beds) reveal site-specific diel, semi-diurnal and stochastic patterns of varying amplitudes as high as 1.0 unit. Nutrient enrichment stimulates primary production and eutrophication (e.g. phytoplankton blooms increase pH to 9.0); however, once die-off occurs, organic matter is remineralized, leading to potential hypoxia and lower pH (Freely *et al.* 2010; Laerent *et al.* 2017). Thus, eutrophication resulting from nutrient pollution severely amplifies the potential ocean acidification signal. It is therefore critical that current sources of nutrient pollution to estuaries and the coast be addressed and no additional future inputs planned, i.e. no additional Wastewater Treatment Works (WWTW) discharges; improve agricultural practises and urban agricultural return flow; eliminate storm water runoff, and no marine aquaculture waste discharges should be allowed in high retention environments such as estuaries.

Measured/modelled water quality conditions of coastal rivers, wetlands and estuaries can be used to report on the proportion of bodies of aquatic ecosystems with good ambient water quality as well as key pollution pressures/sources on these ecosystems as a means of increasing resilience to ocean acidification.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures			
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

SDG Indicator 14.5: By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information

Measured/modelled estuary condition generated as part of an EFlows process can be used to report on the change in the extent of aquatic ecosystems within formally protected areas. EFlows information on the desired state and for estuaries and associated habitats, biota flow, and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures		●	●
Baseline Ecological State/Condition		●	●
Target State/Condition		●	●
EFlows requirements			
Water quality requirements			
Biotic requirements		●	●
Ecosystem services			

Table C.9 Summary of SDG 15 reporting requirements to EFlows outputs

GOAL 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Goal 15 aims include to conserve and restore terrestrial and freshwater ecosystems; restore degraded land; protect biodiversity and natural habitats; prevent invasive alien species on land and in water ecosystems; integrate ecosystem and biodiversity in governmental planning.

This goal aims at securing sustainable livelihoods that will be enjoyed for generations to come. The human diet is composed 80% of plant life, which makes agriculture a very important economic resource. Forests cover 30 percent of the Earth's surface, provide vital habitats for millions of species, and important sources for clean air and water, as well as being crucial for combating climate change

SDG Indicator 15.1: By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements

Measured/modelled condition of rivers, wetlands and estuaries can be used to report on the protection and change in aquatic ecosystems status over time. For this, the type of ecosystems, their extent, how they function, the pressures on them, and their condition and the boundaries of formal protected areas are needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750 before large-scale human interventions). EFlows information on water quantity and quality, biota and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			

Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

SDG Indicator 15.5: Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species."

EFlows information on the desired state for rivers, wetlands and estuaries and associated habitats, biota, and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures			
Baseline Ecological State/Condition			
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

SDG Indicator 15.8: Prevent invasive alien species on land and in water ecosystems

EFlows information on the desired state for rivers, wetlands and estuaries and impact and mitigation to alleviate the impact of biological invasions can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition			
EFlows requirements			
Water quality requirements			
Biotic requirements	●	●	●
Ecosystem services			

SDG Indicator 15.9: Integrate ecosystem and biodiversity in governmental planning Indicator 15.9.1 is "Progress towards national targets established in accordance with Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020" addresses the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society. The target is to have all biodiversity values integrated into national and local development by 2020 as well the incorporation of planning processes into national reporting systems. By 2020 only half of the parties had made some progress towards their targets. EFlows information on water quantity and quality, biota and ecosystem services can also be used to set/evaluate protection and restoration targets and monitor efforts.			
EFLOWS COMPONENTS THAT CAN INFORM REPORTING			
EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			
Resource delineation (geographic extent)			
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services			

C.1.4. Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar) (1971)

Table C.10 Summary of Ramsar reporting requirements that incorporate EFlows outputs

CONVENTION ON WETLANDS OF INTERNATIONAL IMPORTANCE ESPECIALLY AS WATERFOWL HABITAT (RAMSAR) (1971)
The broad aims of this Convention are to stem the loss and promote the wise use of all wetlands. The Convention defines wetlands as *'areas of marsh, fen, peatland or water whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 m'*. The Contracting Parties are required to formulate and implement plans to promote the conservation of wetlands and determine if the ecological character of Ramsar sites has changed, is changing or is likely to change as the result of developments, pollution or other human interference. While the convention promotes the conservation of wetlands and waterfowl by establishing nature reserves on wetlands, it does not stipulate formal protection. Parties are obligated to consult with each other on implementation in the case of a wetland extending over territories or where a water system is shared, with parties required to co-ordinate and support present and future policies and regulations concerning the conservation of wetlands and their flora and fauna.
REQUIREMENTS
Regular conferences are held where parties discuss implementation efforts; changes in the ecological character of wetlands; make recommendations regarding the conservation, management and wise use of wetlands and their flora and fauna; and prepare reports on matters which are affecting wetlands. As part of

their obligations contracting parties are also obligated to report on the Ramsar SDGs. EFlows assessment and allocations are central to the wise use of wetlands and foundational data in the report back on management, protection and use of wetlands. Development pressure data can/is used to highlight areas in need of management or mitigation. Measured/modelled conditions can be used to report on the change in the status of aquatic ecosystems over time. For the Ramsar SDGs information on the ecosystems type, extent, the pressures on them, and their present and the desired condition is needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750). Wetland specific EFlows requirements on flow, water quality, biota and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts. Countries are required to report on both wetlands within Ramsar sites and, if possible, also on the status of all wetlands within their territory. Key habitats such as mangroves are also lifted out for status reporting.
EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements	●	●	●
Ecosystem services	●	●	●

C.1.5. United Nations Convention on Biological Diversity (CBD)

Table C.11 Summary of United Nations Convention on Biological Diversity reporting requirements to EFlows outputs

UNITED NATIONS CONVENTION ON BIOLOGICAL DIVERSITY (1992)
The UN Convention on Biological Diversity came into force in December 1993. It has three objectives: the conservation of biological diversity; the sustainable use of biological resources, and the fair and equitable sharing of benefits arising from the use of genetic resources. The convention recognized for the first time in international law that the conservation of biodiversity is "a common concern of humankind" and is an integral part of the development process. The agreement covers all ecosystems, species and genetic resources. It links traditional conservation efforts to the economic goal of using biological resources sustainably. The convention reminds decision-makers that natural resources are finite and stress the need for sustainable use. While past conservation efforts were aimed at protecting species and habitats, the convention recognizes that ecosystems, species and genes must be used for the benefit of humans, but that this should be done in a way and at a rate that does not lead to the long-term decline of biological diversity.
REQUIREMENTS

Countries party to the Convention are required to develop national strategies, plans or programmes, or adapt existing ones, to address the provisions of the Convention, and to integrate the conservation and sustainable use of biodiversity into sectoral and cross-sectoral plans, programmes and policies. Two key responses are:

- *National Biodiversity Strategies and Action Plans (NBSAP):* NBSAPs are the principal instruments for implementing the Convention at the national level. The Convention requires that all countries prepare a national biodiversity strategy and to ensure that this strategy is included in planning for activities in all sectors where diversity may be impacted.
- *National Reports:* Parties are to prepare national reports on the status of implementation of the convention.

Development pressure data are used to highlight areas in need of management or mitigation. Measured/modelled aquatic ecosystems condition are used to report on the change in aquatic ecosystems over time (with a focus on condition in protected or desired protected areas). For this the type of ecosystems, their areal extent (through delineation and mapping), how they function, the pressures on them, and their condition is needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750 before large scale human interventions). EFlows information on flow, water quality, biota and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition	●	●	●
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

A Strategic Plan for Biodiversity (called the Strategic Plan for Biodiversity 2011-2020 – Aichi Biodiversity Targets) (https://www.cbd.int/sp/) was also developed under the CBD, which has now been largely replaced by the SDGs (Table C.12).

Table C.12 Summary of Aichi Biodiversity Targets reporting requirements to EFlows outputs

STRATEGIC PLAN FOR BIODIVERSITY 2011-2020
Strategic Plan for Biodiversity, 2011-2020 was developed under the United Nations Convention on Biological Diversity (1992). This document included the "Aichi Biodiversity Targets", comprising 20 targets that address each of five strategic goals defined in the Strategic Plan. The strategic plan includes the following strategic goals: address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society; reduce the direct pressures on biodiversity and promote sustainable use; improve the status of

biodiversity by safeguarding ecosystems, species and genetic diversity; enhance the benefits to all from biodiversity and ecosystem services; and enhance implementation through participatory planning, knowledge management and capacity building.			
REQUIREMENTS			
These targets have been replaced by the SDGs. In past aquatic ecosystem typology, extent and condition data derived from regional EFlows assessment were used to populate the indicators where available. However, given the slow up take of some of the Aichi targets there is cross-reference to the historical targets set in the Agenda 2030 – 'SDG sub-indicator 15.9.1 (a) Number of countries that have established national targets in accordance with or similar to Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020 in their national biodiversity strategy and action plans and the progress reported towards these targets'			
EFLOWS COMPONENTS THAT CAN INFORM REPORTING			
EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function			
Pressures			
Baseline Ecological State/Condition			
Target State/Condition			
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

C.1.6. IUCN Red List of Ecosystems (RLE)

Table C.13 Summary of IUCN Red List of Ecosystems requirements to EFlows outputs

IUCN RED LIST OF ECOSYSTEMS (RLE)
The IUCN Red List of Ecosystems (RLE) is a framework for assessing the risks to ecosystems and identifying where ecosystems are threatened (Rodríguez *et al.* 2011). Based on a set of criteria and thresholds developed collaboratively since 2008, the IUCN RLE was established to ensure that the assessment methods are transparent, comparable, repeatable and scientifically rigorous and can be applied systematically across realms and geographic areas. The IUCN RLE complement the IUCN Red List of Threatened Species framework (Bland *et al.* 2017; Keith *et al.* 2013, 2020; Rodríguez *et al.* 2011, 2015).
REQUIREMENTS
The goal of the IUCN RLE is to identify ecosystems that are at risk of losing their constituent biodiversity (Keith *et al.* 2013, Bland *et al.* 2017). The RLE requires clearly defined units of assessments (ecosystem types) that can be delineated spatially, but also allows for the assessment of risks effectively across a widely range of ecosystem types (Keith *et al.* 2013). The RLE framework used the concept of ecosystem collapse as the "end point" of ecosystem decline, this is equivalent to species extinction in the Red List of Species, and is defined operationally as a "transformation of identity, loss of defining abiotic or biotic features and characteristic

native biota are no longer sustained" (Keith *et al.* 2013). Declining distributions and restricted distributions are considered distributional symptoms of decline; and degradation of abiotic environment and altered biotic function are considered functional symptoms of decline. The mechanisms in the conceptual model of ecosystem collapse translate into five rule-based criteria with thresholds for the distributional and functional symptoms. Key aquatic biomes that can utilise EFlows assessment outputs following the IUCN Global Ecosystem Typology (GET) include:

- TF1 Palustrine wetlands biome (IUCN GET code TF1.4 Seasonal floodplain marshes)
- F1 Rivers and streams biome (e.g. F1.1 Permanent upland streams, F1.5 Seasonal lowland rivers, F1.6 Episodic arid rivers)
- F2 Lakes biome (e.g. Large permanent freshwater lakes, F2.3 Seasonal freshwater lakes)
- F3 Artificial wetlands biome (e.g. F3.1 Large reservoirs)
- FM1 Semi-confined transitional waters biome (e.g. FM1.2 Permanently open riverine estuaries and bays, FM1.3 Intermittently closed and open lakes and lagoons)
- MT1 Shorelines biome (e.g. MT1.2 Muddy shorelines)
- MFT1 Brackish tidal biome (e.g. MFT1.1 Coastal river deltas, MFT1.2 Intertidal forests and shrublands)

Measured/modelled condition can be used to report on the change in the extent of aquatic ecosystems over time with a focus on the extent and water quantity (e.g. South Africa has been pilot-testing this approach). For RLE the type of ecosystems, their extent, a conceptual model of ecosystem function, key pressures on them, and their condition is needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition, defined as 1750. Assessment periods are generally 50 years, with future projected decline also considered as possible criteria.

EFlows information on decline inflow, water quality, biotic components and change ecosystem services provide critical input data sets to the RLE process.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function	●	●	●
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition			
EFlows requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services	●	●	●

C.1.7. United Nations Framework Convention on Climate Change (UNFCCC) and Paris Agreement

Table C.14 Summary of UNFCCC reporting requirements to EFlows outputs

<table>
<tr><td colspan="4">UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (1992)</td></tr>
<tr><td colspan="4">The United Nations Framework Convention on Climate Change (UNFCCC) took effect in March 1994 and sets an "ultimate objective" of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Countries ratifying the Convention agree to take climate change into account in such matters as agriculture, energy, natural resources, and activities involving sea and coasts. They agree to develop national programmes to slow climate change. The Convention encourages parties to cooperate to reduce greenhouse gas emissions, share technology and carry out scientific research. The Kyoto Protocol was the first international agreement to be established under the UNFCCC (United Nations 1998). The Paris Agreement expands on the Kyoto Protocol and serves as a framework for establishing a global carbon market. The Paris Agreement will replace the Kyoto Protocol once the second commitment period of the latter ends in 2021. The Paris Agreement has a central aim to keep global temperature to less than 2°C (preferably less than 1.5°C) above pre-industrial levels.
Towards this, Nationally Determined Contributions (NDC) are compiled by countries to outline their efforts to address climate change mitigation and adaptation. Each country is to develop their NDC with mitigation and adaptation actions based on a series of measures, including nature-based solutions such as the conservation and restoration of ecosystems. As part of this process countries are required to develop carbon registers, including the mapping of habitats that sequester carbon.</td></tr>
<tr><td colspan="4">REQUIREMENTS</td></tr>
<tr><td colspan="4">Blue and Teal carbon ecosystems associated with aquatic ecosystems should/can be incorporated into mitigation actions because of their carbon storage and sequestration potential (Siikamäki <i>et al.</i> 2012). Blue Carbon ecosystems should also be included in adaptation actions as they provide natural coastal protection from storm surges and sea-level rise, as well as additional co-benefits such as nursery habitats for fish and invertebrate species, water purification, and support to local livelihoods.
‘Blue carbon’ refers to the carbon found in three coastal biotic habitats: mangroves, seagrasses, and salt marshes. In addition, carbon is also stored in swamp forest, reeds and sedges – what is generally referred to as ‘Teal carbon’ associated with freshwater wetland habitats. These habitats sequester carbon from the atmosphere and lock it into the soil. These habitats are unique in that the carbon that they sequester during photosynthesis is often moved from the short-term carbon cycle (10-100 years) to the long-term carbon cycle (1000 years) and is continuously buried as slowly decaying biomass (Barbier <i>et al.</i> 2011).
Blue and Teal carbon ecosystems thus present an opportunity to contribute towards climate change mitigation and adaptation strategies because of their efficiency to sequester atmospheric CO_2 and the long-term storage of organic C. Losses of these ecosystems (either by degradation, or complete removal and conversion) in turn represent not only a loss of the natural carbon sink capacity, but also a contribution towards greenhouse gas emissions.
As part of the EFlows assessment process, information is gathered on the extent, pressures and condition of these rare ecosystem types. EFlows information on flow, water quality, and biotic responses can also be used to set/evaluate restoration targets and monitor efforts.</td></tr>
<tr><td colspan="4">EFLOWS COMPONENTS THAT CAN INFORM REPORTING</td></tr>
<tr><td rowspan="2">EFlows components</td><td colspan="2">Freshwater ecosystems</td><td>Coastal ecosystems</td></tr>
<tr><td>Rivers</td><td>Inland wetlands</td><td>Estuaries</td></tr>
</table>

Ecosystem typology		●	●
Resource delineation (geographic extent)		●	●
Model (conceptual/numeric) of ecosystem function			
Pressures		●	●
Baseline Ecological State/Condition		●	●
Target State/Condition		●	●
Flow requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

C.1.8. Global Environment Outlook (GEO) and other national or regional level state of the environment reporting processes

Table C.15 Summary of GEO reporting requirements to EFlows outputs

GLOBAL ENVIRONMENT OUTLOOK (GEO)

Global Environment Outlook (GEO) is a series of reports on the environment issued by the United Nations Environment Programme (UNEP). The GEO report series was initiated in response to the environmental reporting requirements of UN Agenda 21 and a UNEP Governing Council request for a comprehensive global state of the environment report as far back as 1995. Six GEO reports have been published to date between 1997 and 2019.

A global network of collaborating centres coordinate process, with regional centres responsible for regional inputs, combining top-down integrated assessment with bottom-up environmental reporting. Working groups provide advice and support to the GEO process, particularly on integrated assessment methodologies and process planning.

Other outputs of the GEO project include regional, sub-regional and national integrated environmental assessments, technical and other background reports, a website, products for young people and a core database – the GEO Data Portal.

REQUIREMENTS

As part of this reporting process countries are required to provide a status assessment of freshwater and marine ecosystems at the national scale.

Status information generated as part of the EFlows process at regional/strategic scales is key to this level of reporting. Development pressure data can/is used to highlight areas in need of management or mitigation. While measured/modelled aquatic ecosystems condition can be used to report on the change in aquatic ecosystems over time. For this the type of ecosystems, their geographic / areal extent (delineation), how they function, the pressures on them, and their condition is needed. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750 before large scale human interventions).

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries

Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Baseline Ecological State/Condition	●	●	●
Target State/Condition			
Flow requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

C.1.9. UN System of Environmental-Economic Accounting (SEEA)

Table C.16 Summary of SEEA reporting requirements to EFlows outputs

UN SYSTEM OF ENVIRONMENTAL-ECONOMIC ACCOUNTING
Society derives invaluable benefits from ecosystems. In recognition of the strong coupling between human-nature systems the concept of 'ecosystem services' emerged which has become a common lens used in science, management and governance, to explicitly link ecological infrastructure with benefits to societies and economies. In 2012 the UN launched the first international statistical framework for the environment, the System of Environmental-Economic Accounting (SEEA), as a counterpart to the System of National Accounts (SNAs) (UN *et al.* 2014a, 2014b; UN 2017). The SEEA is a framework for capturing and organising information on the environment, including its contribution to socio-economic activities and the impact of socio-economic activities on the environment. The framework is based on internationally agreed accounting concepts in terms of gathering and organising information in a consistent manner that enables integration with socio-economic information such as the SNAs. Ecosystem accounting, a subset of Natural Capital Accounting, aims to quantify and track changes in ecosystem assets and ecosystem services over time. It is intended to inform a range of policy, planning and decision-making processes relating to the management of ecosystems and the use of ecosystems services, as well as to enable links to be made between the measurement of ecosystems and the measurement of the economy. Ecosystem accounts can support strategic decision making in natural resources management and assist with trade-offs between different ecosystem services, for example in the food-water-energy nexus. Ecosystem accounting can also provide a powerful set of indicators for measuring and reporting on sustainable development and progress in resource protection.
REQUIREMENTS
Ecosystem Accounting measurement of stocks of ecosystem (or natural capital) assets, its condition, flows of services and goods provided by such assets, and its estimated value to communities, governments and businesses (based on either market transactions or non-market valuation) (UN 2017). Ecosystem accounting can be applied at different scales for different purposes. For example, at the national and international level, accounts can be used for raising awareness of the benefits derived from natural ecosystems, reporting on Sustainable Development Goals, or setting estuary management priorities. At the provincial or local scales, accounts can be used to inform resource allocation (e.g. freshwater flow or fisheries allocations), progress in restoration projects or to evaluate impacts of policies and programmes at regional levels.

Status information generated as part of the EFlows process at regional/strategic scales are key to the development of aquatic ecosystems accounts, with extent, condition used to report on the change in aquatic ecosystems over time, examples are provided by Nel and Driver (2015) and van Niekerk *et al.* (2020). For this the type of ecosystems, their extent (delineation), how they function, the pressures on them, and their condition is needed. Information on ecosystem services can be used in Ecosystem services supply and use accounts.

EFLOWS COMPONENTS THAT CAN INFORM REPORTING

EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology	●	●	●
Resource delineation (geographic extent)	●	●	●
Model (conceptual/numeric) of ecosystem function			
Pressures	●	●	●
Ecological State/Condition	●	●	●
Desired State/Condition			
Flow requirements			
Water quality requirements			
Biotic requirements			
Ecosystem services			

In addition to the national/regional SADC level obligations highlighted above, the result of EFlows assessments can also be integrated into a range of lower-level applications, namely:

- Biodiversity/Protected Areas Planning: Water Resource condition and desired states are critical input data sets in the development of a network of protected areas that generally target natural/near-natural ecosystems or systems deemed irreplaceable.
- Strategic Environmental Assessments (SEA): Regional-scale EFlows assessments prove fundamental data sets for SEA processes as they provide estimates of water resources available for future development and highlight the desired state of water resources as management objectives.
- Environmental Impact Assessments (EIA): The acceptability for future land-use change and development should be measured against the aquatic resource targets set for a basin and water management area. It found wanting the development should not be approved
- Research and Education: The outputs of EFlows assessment can be both be supported by academic research and feed into research and educational strategies. EFlows studies provide opportunities to develop field experience and test proposed research approaches.

C.1.10. Nairobi and Abidjan Conventions

Table C.17 Summary of Nairobi Convention requirements to EFlows outputs

CONVENTION ON THE PROTECTION, MANAGEMENT AND DEVELOPMENT OF THE MARINE AND COASTAL ENVIRONMENT OF THE EAST AFRICAN REGION (NAIROBI CONVENTION) (1985)			
The convention focuses on standardisation of coastal management in the East African region. The broad objectives of the convention are the development, protection and management of the coastal and marine environment. It requires that environmental management issues are identified for which co-operative efforts are to be made, which include specially protected areas, co-operation in cases of emergencies, mitigation of environmental damage from engineering activities, undertaking of Environmental Impact Assessments (EIAs) and promoting scientific and technical co-operation (UNEP-Nairobi Convention/WIOMSA 2020). Parties are to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other marine life in specially protected areas and to cooperate in dealing with pollution emergencies.			
REQUIREMENTS			
The Convention lists sources of pollution that require control such as pollution from ships, dumping, land-based sources and exploitation of the seabed together with airborne pollution. Parties are also to take measures to prevent, reduce and combat environmental damage from dredging, land reclamation, and other engineering activities. Towards this more recently EFlows guidelines were developed for the region. While no formal regional scale reporting is required the various members parties signatory to the convention regularly report on the state of coastal biodiversity, with a focus on mangroves and seagrass habitats and coastal fish resources. More recently the Convention developed the "Guidelines on Environmental Flows (EFlows) Assessments for the Western Indian Ocean (WIO) region: in response to ongoing decline in the estuary and coastal environment as a result of catchment development. Regional-scale reporting on coastal conditions can/may use ecosystem type ecosystems, extent, how they function, the pressures on them, and their condition to highlight areas in need of management or mitigation. For EFlows assessment to be useful in this regard, one of the benchmark scenarios assessed needs to be the natural condition (<1750 before large scale human interventions). In addition, assessment needs to be at regional scales, albeit of low confidence for under-developed water resources. EFlows information on flow, water quality, biota and ecosystem services can also be used to set/evaluate restoration targets and monitor efforts.			
EFLOWS COMPONENTS THAT CAN INFORM REPORTING			
EFlows components	Freshwater ecosystems		Coastal ecosystems
	Rivers	Inland wetlands	Estuaries
Ecosystem typology			●
Resource delineation (geographic extent)			●
Model (conceptual/numeric) of ecosystem function			
Pressures			●
Baseline Ecological State/Condition			●
Target State/Condition	●	●	●
Flow requirements	●	●	●
Water quality requirements	●	●	●
Biotic requirements			●
Ecosystem services			●

Table C.18 Summary of Abidjan Convention requirements to EFlows outputs

<table>
<tr><td colspan="4">CONVENTION ON THE PROTECTION, MANAGEMENT AND DEVELOPMENT OF THE MARINE AND COASTAL ENVIRONMENT OF THE WEST AND CENTRAL AFRICAN REGION (ABIDJAN CONVENTION 1981)</td></tr>
<tr><td colspan="4">The Convention focuses on the standardization of coastal management in the West and Central African region – a coastline / coastal region extending just over 14,000 kilometres along the coast. The broad objectives of the Convention are the development, protection and management of the coastal and marine environment. It requires that environmental management issues are identified for which co-operative efforts are to be made, which include specially protected areas, co-operation in cases of emergencies, mitigation of environmental damage from engineering activities, undertaking of EIAs and promoting scientific and technical co-operation.

The coastal waters within the convention area contain highly productive ecosystems that support rich fisheries. However, serious conflicts have resulted in immense human suffering and poverty. In the last three decades or so, the rapid development, improper use of resources and extensive pollution has harmed coastal ecosystems. Coastal erosion and floods are key problems, likely to be exacerbated by climate change. Destruction of critical habitats is widespread in the convention area, and coastal communities are both the perpetrators and victims of the destruction.</td></tr>
<tr><td colspan="4">REQUIREMENTS</td></tr>
<tr><td colspan="4">While the convention lists sources of pollution that require control such as pollution from ships, dumping, <u>land-based sources</u> and seabed activities together with airborne pollution, no efforts have been made along this region to integrate it with EFlows requirements.

However, estuary ecosystems pressure and condition data (derived from EFlows assessments) are used to report on the change in aquatic ecosystems over time where available.

Efforts should be made to integrate EFlows assessment and IWRM into regional-scale planning processes under this Convention as there are significant water resource development pressures on the Orange-Senqu and Kunene basins.</td></tr>
<tr><td colspan="4">EFLOWS COMPONENTS THAT CAN INFORM REPORTING</td></tr>
<tr><td rowspan="2">EFlows components</td><td colspan="2">Freshwater ecosystems</td><td>Coastal ecosystems</td></tr>
<tr><td>Rivers</td><td>Inland wetlands</td><td>Estuaries</td></tr>
<tr><td>Ecosystem typology</td><td></td><td></td><td>●</td></tr>
<tr><td>Resource delineation (geographic extent)</td><td></td><td></td><td>●</td></tr>
<tr><td>Model (conceptual/numeric) of ecosystem function</td><td></td><td></td><td></td></tr>
<tr><td>Pressures</td><td></td><td></td><td>●</td></tr>
<tr><td>Baseline Ecological State/Condition</td><td></td><td></td><td>●</td></tr>
<tr><td>Target State/Condition</td><td></td><td></td><td></td></tr>
<tr><td>Flow requirements</td><td></td><td></td><td></td></tr>
<tr><td>Water quality requirements</td><td></td><td></td><td></td></tr>
<tr><td>Biotic requirements</td><td></td><td></td><td></td></tr>
<tr><td>Ecosystem services</td><td></td><td></td><td></td></tr>
</table>

C.2. Using global reporting processes as a reporting/evaluation framework at the water basin /management area scale

C.2.1. Sustainable Development Goals

At the project level scale, EFlows future development scenarios should also be evaluated against the 17 SDGs to evaluate the degree to which future developments contribute towards achieving SDGs at the basin scale (Table C.19). Important indicators are highlighted.

Table C.19 SDG indicators at the basin scale

APPLICABLE SDG GOAL AND ASSOCIATED SUB-INDICATORS	INFORMATION NEED/DATA GAP AT THE WATER BASIN / MANAGEMENT AREA SCALE
GOAL 1: NO POVERTY 1.4.1 Proportion of population living in households with access to basic services	Indicate # of households that will be supplied with clean running water (current and planned)
GOAL 2: ZERO HUNGER 2.4.1 Proportion of agricultural area under productive and sustainable agriculture	Indicate extend of the area under current and future water resource development for food production (current and planned)
GOAL 3: GOOD HEALTH AND WELL-BEING 3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services)	Indicate the current and projected mortality rate attributed to unsafe water unsafe sanitation and lack of hygiene
GOAL 4: QUALITY EDUCATION	-
GOAL 5: GENDER EQUALITY	
5.5.2 Proportion of women in managerial positions	Report on the number of women in managerial positions within the water basin/management area (current and planned)
5.a.1 (a) Proportion of total agricultural population with ownership or secure rights over agricultural land, by sex; and (b) share of women among owners or rights-bearers of agricultural land, by type of tenure	Report on the present (and planned) % female ownership of the agricultural areas
GOAL 6: CLEAN WATER AND SANITATION	
6.1.1 Proportion of population using safely managed drinking water services	Report on the proportion of the population using well managed drinking water services in water basin/management area (current and planned)
6.3.1 Proportion of domestic and industrial wastewater flows safely treated	Report on the proportion of domestic and industrial wastewater flows treated to stated standard in water basin/management area (current and planned)
6.3.2 Proportion of bodies of water with good ambient water quality	Report on the proportion of bodies of water with good ambient water quality in water basin/management area (current and planned)

APPLICABLE SDG GOAL AND ASSOCIATED SUB-INDICATORS	INFORMATION NEED/DATA GAP AT THE WATER BASIN / MANAGEMENT AREA SCALE
6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Report on the level of water stress freshwater resources: freshwater withdrawal as a proportion of available freshwater resources in water basin/management area (current and planned)
6.5.1 Degree of integrated water resources management	Report on the degree of integrated water resources management in the water basin/management area (current and planned)
6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation	Report if operational transboundary basin agreements are in place for shared river systems
6.6.1 Change in the extent of water-related ecosystems over time	Indicate the % change in the extent of aquatic ecosystems over time (current and planned)
6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management	Indicate proportion of local administrative units with established and operational policies and procedures within which of local communities participate in water and sanitation management in water basin/management area
GOAL 7: AFFORDABLE AND CLEAN ENERGY 7.b.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)	Report on present (and proposed) renewable energy-generating capacity within the water basin/management area
GOAL 8: Decent Work and Economic Growth	
8.1.1 Annual growth rate of real GDP per capita	Indicate % increase in water basin/management area GDP per capita (current and planned)
8.3.1 Proportion of informal employment in total employment, by sector and sex	Indicate % increase in informal employment by sector and sex (current and planned)
8.5.2 Unemployment rate, by sex, age and persons with disabilities	Indicate % increase in jobs by sector and sex (current and planned)
GOAL 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE	
9.3.1 Proportion of small-scale industries in total industry value added	Report on potential economic gains/losses associated with basin development
9.4.1 CO2 emission per unit of value added	Report on the loss of blue (coastal) and teal (freshwater) carbon habitats and associated carbon emissions as a result of water resource development (current and planned)
GOAL 10: REDUCED INEQUALITY 10.2.1 Proportion of people living below 50 per cent of median income, by sex, age and persons with disabilities	Report on demographics in region and potential economic gains/losses that will be experienced by the most vulnerable groups.
GOAL 11: SUSTAINABLE CITIES AND COMMUNITIES 11.3.1 Ratio of land consumption rate to population growth rate	Indicate land consumption to population growth rate ratio under development scenarios (current and planned)

APPLICABLE SDG GOAL AND ASSOCIATED SUB-INDICATORS	INFORMATION NEED/DATA GAP AT THE WATER BASIN / MANAGEMENT AREA SCALE
GOAL 12: RESPONSIBLE CONSUMPTION AND PRODUCTION	
12.a.1 Installed renewable energy-generating capacity in developing countries (in watts per capita)	Indicate if any renewable energy-generating capacity is part of future water resource development scenarios
2.b.1 Implementation of standard accounting tools to monitor the economic and environmental aspects of tourism sustainability	Develop environmental accounting /water accounts to reflect past and future changes in water resource status and yield
GOAL 13: CLIMATE ACTION	
13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans, strategies as reported in adaptation communications and national communications	Incorporate climate change in the range of future water resource development scenarios
13.2.2 Total greenhouse gas emissions per year	Report on the loss of blue and teal carbon habitats and associated carbon emissions as a result of water resource development, e.g. degraded land represents an ongoing emission (current and planned)
GOAL 14: LIFE BELOW WATER	
14.1.1 (a) Index of coastal eutrophication; and (b) plastic debris density	Report % coastal ecosystem type subjected to eutrophication as a result of enrichment from land-based sources. Indicate what % is of fluvial origin (current and planned)
14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	Indicate the degree/extent of coastal acidification occurring along the coast. Indicate what % is of fluvial origin.
14.4.1 Proportion of fish stocks within biologically sustainable levels	Report if estuarine associated and estuarine dependent species are managed at sustainable levels & to what degree water resource development is/will contributing to depletion/slow stock recovery.
14.5.1 Coverage of protected areas in relation to marine areas	Calculate % good condition estuaries and fluvially-dependant nearshore environments within formally protected areas (poor condition systems can not contribute 100% to this indicator) (current and planned) Indicate if small-scale fisheries were given access into EFlows processes, including addressing issues of language, education and scientific knowledge transfer.
14.b.1 Degree of application of a legal/regulatory/policy/institutional framework	Indicate if small-scale fisheries were given access into EFlows processes, including addressing issues of

APPLICABLE SDG GOAL AND ASSOCIATED SUB-INDICATORS	INFORMATION NEED/DATA GAP AT THE WATER BASIN / MANAGEMENT AREA SCALE
which recognizes and protects access rights for small-scale fisheries	language, education and scientific knowledge transfer.
GOAL 15: LIFE ON LAND	
15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type	Indicate % biodiversity hot spots in formally protected areas (with an adequate flow allocation) (current and planned)
15.3.1 Proportion of land that is degraded over total land area	Indicate % degraded land over water basin/management area (and possible improvement under future scenarios) (current and planned)
15.5.1 Red List Index	Report on the number of red listed species and ecosystems in water basin/management area. Indicate if water resource development is likely to increase/decrease threat status.
15.8.1 Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species	Report on increase/decrease risk of introducing invasive alien species and associated impact on aquatic ecosystems
15.9.1 (a) Number of countries that have established national targets in accordance with or similar to Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020 in their national biodiversity strategy and action plans and the progress reported towards these targets; and (b) integration of biodiversity into national accounting and reporting systems, defined as implementation of the System of Environmental-Economic Accounting	a) Report on progress with achieving Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020 for water basin/management area (current and planned b) Develop a set of aquatic ecosystems accounts to reflect change in extent, condition and flow of ecosystem services.
GOAL 16: PEACE AND JUSTICE STRONG INSTITUTIONS 16.6.1 Primary government expenditures as a proportion of original approved budget, by sector (or by budget codes or similar)	Report on infrastructure expenditure required for water resource development (current and planned)
GOAL 17: PARTNERSHIPS TO ACHIEVE THE GOAL 17.7.1 Total amount of funding for developing countries to promote the development, transfer, dissemination and diffusion of environmentally sound technologies	Report the contribution from international funding bodies to EFlows assessment and infrastructure development (current and planned)

C.2.2. Global Reporting Initiative (GRI) Standards

In addition to potential reporting frameworks, globally there have also been developments in reporting standards (Table C.20).

Table C.20 Summary of GRI Reporting standards relevant to EFlows assessments

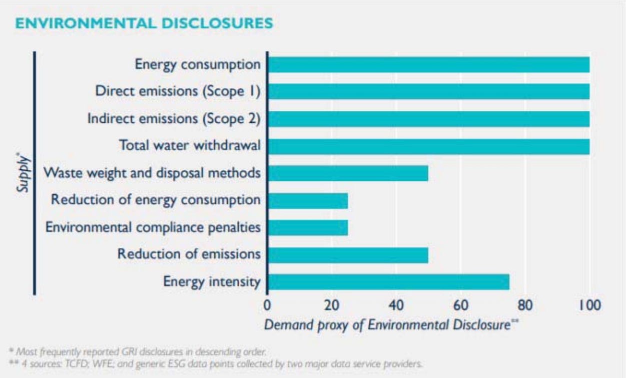
Global Reporting Initiative (GRI) Standards

The GRI Standards create a common language for organizations to report on their sustainability impacts consistently and credibly to enhances global comparability and enables transparency and accountability (https://www.globalreporting.org/standards).

The Standards help organizations understand and disclose their impacts in a way that meets the needs of multiple stakeholders. The Standards are highly relevant to many groups, including investors, policymakers, capital markets, and civil society. The Standards are designed as an easy-to-use modular set, starting with the Universal Standards. Topic Standards are then selected based on the organization's material topics – economic, environmental or social. This process ensures that the sustainability report provides an inclusive picture of material topics, their related impacts, and how they are managed. Specifically, the GRI is highlighting the growing demand from investors for companies to be more transparent on their environmental impacts, such as greenhouse gas emissions or water use, and to take actions to improve their environmental performance. The GRI also emphasises the importance and advantages of considering private-sector environmental, social and governance (ESG), specifically climate change information, when taking investment decisions. Investors are currently calling for standardization, verifiability and increased clarity on the scope of sustainability disclosures and are searching for or developing context-based metrics.

REQUIREMENTS

Key environmental disclosures for large projects include for example below (GRI 2019):



* Most frequently reported GRI disclosures in descending order.
** 4 sources: TCFD; WFE; and generic ESG data points collected by two major data service providers.

Detail on GRI Standards

Reporting and/or declaration have been developed for two critical areas relevant to EFlows assessments, namely Water and Effluent (GRI 303) and Greenhouse Gas Emissions (GRI 305).

GRI 303: WATER AND EFFLUENTS 2018 (GRI 2018)	GRI 305: EMISSIONS 2016 (GRI 2016)
Interactions with water as a shared resource Management of water discharge-related impacts Water withdrawal Water Discharge Water Consumption	Water Discharge G4: Effluents and Waste GRI 306: Effluents and Waste Water Consumption Direct (Scope 1) GHG emissions Energy indirect (Scope 2) GHG emissions Other indirect (Scope 3) GHG emissions GHG emissions intensity Reduction of GHG emissions Emissions of ozone-depleting substances (ODS) Nitrogen oxides (NOx), sulphur oxides (SOx), and other significant air emissions