THE DEVELOPMENT OF A STRATEGY FOR THE WATER RESEARCH COMMISSION THRUST "ENVIRONMENTAL FUNCTIONING WITHIN THE HYDROLOGICAL CYCLE" WITHIN THE CROSSCUTTING DOMAIN "WATER AND THE ENVIRONMENT"

- PHASES 1 & 2

by

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Report to the Water Research Commission on the project
Development of the research strategy for the WRC domain "Water and the Environment" to project level – Phase 2: Review of national research portfolio related to water and the environment (WRC project number K8/584)

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EXECUTIVE SUMMARY

This report is a contribution to the development of an investment strategy for the Water Research Commission (WRC) for Thrust 1: *Environmental Functioning within the Hydrological Cycle* within the Crosscutting Domain: *Water and the Environment*. The objective of this domain is to contribute to achieving a situation where our governance systems and our understanding of environmental processes and functioning are aligned to support sustainable water resources management that meets the needs of society.

This review focuses on that part of the domain objective that centres on our understanding of environmental processes and functioning, i.e. Thrust 1: *Environmental Functioning within the Hydrological Cycle*. Environmental processes and functioning have been described in the context of the components of the hydrological cycle (aquatic, terrestrial, subterranean, atmospheric and marine), in that there are biophysical, biochemical and ecological links within and between each of these components. This means that water resources are linked, via the water itself, to broader environmental processes and functioning, and respond to all forms of human activities.

Incomplete knowledge and understanding of the linkages between the components of the hydrological cycle hinders achievement of domain objectives, and prevents society from accomplishing the broader goal of sustainable water resources management. This review evaluates the extent of our existing knowledge base related to the environmental processes and functions that occur within and between the components of the hydrological cycle, and seeks to identify those knowledge gaps that preclude a complete understanding of processes within the hydrological cycle. The review has been divided into two phases, where phase 1 comprised a review of the WRC's contribution to the domain objective, and phase 2 covered the contributions from the Department of Water Affairs & Forestry (DWAF). This report describes the results of both phases.

It must be recognised that the WRC and DWAF only contribute to a segment of knowledge that comprises the domain objective. Many other institutions also participate in research that supports and contributes to the WRC achieving its domain objective. In addition, a similar review has been conducted for Thrust 2 of the domain, which focuses on *Environmental Governance Systems* (Pegasys, 2005). These two reviews will feedback into the Domain's draft investment strategy (MacKay et al., 2004) and will help to determine those research issues that will be prioritised for future investment. In determining the pool from which to source publications relevant to the scope of the *Environmental Functioning Within the Hydrological Cycle* thrust, the list of publications from the Water Research Commission was analysed and a search using the NISC database was undertaken. Those publications that were considered to be relevant to the domain were selected for input into a database. The database provides a brief outline or summary of the research undertaken, together with a list of referencing details, the identification of any relationships between the research and the WRC priority issues, and a list of the associated components of the hydrological cycle that were studied.

The database contains 855 records, 625 records from the WRC and 230 from DWAF. Each record was categorised in terms of its relationship to the components of the hydrological cycle; of the 855 records, 470 were categorised as aquatic, 136 as terrestrial, 121 as subterranean, 49 as atmospheric, 8 as marine, and 71 were unclassified current projects. When this dataset is analyzed per decade (starting in 1970 and ending in 2009), it is clear that the majority of research projects funded by DWAF that are relevant to the thrust *Environmental Functioning Within the Hydrological Cycle,* were conducted in the 1970s and 1980s and the majority of those funded by the WRC were conducted from 1990 to the present time.

In addition, a list of priority issues was developed from the thrust and programmes that were identified during the development of a strategy for the domain *Water and the Environment*, within the thrust *Environmental Functioning Within the Hydrological Cycle*. These issues are believed to represent the most important current, emerging or foreseeable concerns related to water in the environment in the next 3 to 8 years. Each record entered into the database was assigned one or more issues that were

regarded as relevant to the research undertaken. A total of 27 issues were identified and grouped into six programmes. A brief description of the scope of each programme is listed below.

Programme 1: Regional and global-scale changes in the (biophysical) environment
Changes in the broader environment at regional and global level may lead to significant long-term impacts on some or all of the components of the hydrological cycle. This includes the impacts of climate change on hydrology, water quality, biodiversity and ecosystem functions, as well as the impacts of regional processes such as desertification, urbanization, and the migration of populations due to political, social, economic or environmental pressures (including HIV/Aids). This programme focuses on understanding the scope and significance of potential impacts of regional and global scale processes on environmental components and processes within the hydrological cycle, and hence on the availability, quality and reliability of surface and groundwater resources, and developing appropriate policy responses to these impacts.

Programme 2: Biodiversity
The structural, functional and compositional aspects of biodiversity underpin the resource base from which ecosystem goods and services are derived. However, our understanding of these three aspects of biodiversity, their responses to natural or human-induced change, and their role in sustaining the flow of ecosystem goods and services, remains limited. This programme focuses on understanding the role of biodiversity in sustainable water resources management, the key drivers of changes in biodiversity, the implications for society and the economy of changes in biodiversity in the aquatic, marine, terrestrial, subterranean and atmospheric components of the hydrological cycle, and options for protection of biodiversity. The development of water resource management indicators that better reflect structural, functional and compositional aspects of biodiversity, and which are based on our best scientific understanding of the links between environmental stressors and ecosystem response, is an important activity within this programme.

Programme 3: Impacts and management of introduced species
Deliberate or accidental release of non-indigenous or alien species can have significant impacts on ecosystem structure and function across the hydrological cycle. This includes the introduction of commercial agricultural and forestry species, alien species (particularly those that are invasive), and introductions of genetically modified organisms (GMOs). This programme focuses on understanding the current and potential impacts of introduced species on environmental components and processes within the hydrological cycle, as well as the development of appropriate policy responses and integrated approaches to preventing, managing and mitigating these impacts.

Programme 4: Interfaces
This programme focuses on developing our conceptual and quantitative understanding of biophysical and ecological processes occurring at the interfaces between components of the hydrological cycle, e.g. marine-freshwater, atmospheric-aquatic, groundwater-surface water, in order to identify critical points for management intervention, and to provide information and tools to support integrated management across the hydrological cycle.

Programme 5: Resource Directed Measures (RDM)
This programme focuses on integrating work done within the KSAs on the basic human needs and ecosystem aspects of resource directed measures for protection of water resources (those contained in Chapter 3 of the National Water Act: the classification system, the Reserve and resource quality objectives), and ensuring that the outputs of WRC-funded research are taken up within a co-coordinated national strategy for policy development related to protection of water resources.

WRC Strategic Issues
This programme comprises cross-cutting issues that integrate across all KSAs and domains. It is a dynamic programme that evolves over time in response to current trends and issues. Currently it focuses on the implications of national and regional poverty alleviation on the hydrological cycle and the impact of HIV/Aids on water resource management.

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1. INTRODUCTION

1.1 Water Research Commission Mandate

The Water Research Commission (WRC) is a dynamic hub for water-centred knowledge, innovation and intellectual capital, providing leadership for research and development through the support of knowledge creation, transfer and application. The WRC engages stakeholders and partners in solving water-related problems that are critical to South Africa's sustainable development and economic growth, and is committed to promoting a better quality of life for all.

The WRC vision is to be recognized globally as a leader in providing innovative solutions for sustainable water management that meets the changing needs of society and of the environment.

As stated in its core strategy the WRC will continue to focus on building a sustainable water-related knowledge base in South Africa by:

- Investing in water research and development projects;
- Building sustainable and appropriate capacity;
- Developing competences/skills for the water sector; and
- Forming strategic partnerships in order to achieve objectives more effectively while making optimal use of the latest global information/knowledge and other available technologies.

The core strategy of the WRC calls for specific mechanisms to address key strategic issues of national importance; these are dealt with in four crosscutting domains that have been established specifically for this purpose. During 2002/2003 the importance of these issues was highlighted when they emerged as major issues in the World Summit for Sustainable Development (WSSD) agenda and the newly developed agenda for the New Partnership for Africa's Development (NEPAD). These domains form integrating frameworks that cut across the WRC's Key Strategic Areas (KSAs) and draw together ongoing programmes and projects within the portfolios of each of the KSAs, and address issues relevant to the domains. The crosscutting domains may also drive specific overarching programmes and/or projects that relate to all KSAs in a more general manner.

The crosscutting domains address the following key issues:

- Water and Society;
- Water and the Economy;
- Water and the Environment; and
- Water and Health.

1.2 The Scope of the Crosscutting Domain: Water and the Environment

The close linkages between air, water and land, through the hydrological cycle, ensure that surface and ground water resources are strongly influenced by changes and processes that originate within the broader natural environment. Effective and sustainable management of water resources requires that we recognize and account for natural processes as well as human induced impacts occurring in the natural environment, which influence all phases of the hydrological cycle. This is one of the key principles of Integrated Water Resource Management (IWRM), which underpins South Africa's water policy and legislation.

Incomplete knowledge and understanding of the linkages between environmental components (atmospheric, marine, terrestrial, aquatic, subterranean) within the hydrological cycle, and between the hydrological cycle and governance systems, hinders sustainable water resources management. The crosscutting domain: Water and the Environment promotes enhanced understanding of whole-ecosystem functioning in the context of the broader environment and its effects on water resources,

and supports the development and application of good environmental governance systems. Activities within this domain contribute to sustainable water resources management that meets the changing needs of society, by combining:

- Our understanding of good governance principles; with
- Our knowledge of environmental components (atmospheric, marine, terrestrial, aquatic, subterranean) and processes within the hydrological cycle.

The primary focus of the domain will be to integrate existing and new insights that are generated by research within and between the KSAs and by other institutions working in related fields. In addition, this domain will stimulate the generation of specific new knowledge and understanding that will equip the water sector to anticipate and respond appropriately to changes within the biophysical environment. Although this domain is characterized by integrating research at a high / meta-data analysis level, it is recognized that such research is only possible on the assumption that we continue to have a sound foundation of appropriate basic research (and data) in place.

The objective of the domain is to contribute to achieving a situation where our governance systems and our understanding of environmental processes and functioning are aligned to support sustainable water management that meets the needs of society.

1.3 Approach to the Development of a Research Strategy for the Domain

An earlier background paper (Ashton et al., 2002) addressed two of the original thrust areas within the *Water and the Environment* domain, namely: *Environmental Governance* and *Biodiversity Protection and Environmental Functioning*. The primary purpose of the background paper was to serve as an introductory document to support a process of identifying the central issues related to environmental governance, biodiversity protection and ecosystem functioning, particularly as they relate to *the management of water in the environment*. This was intended to help position WRC research investments in this arena so that they can make a meaningful contribution to ensuring healthy ecosystem functioning and effective water resources management on a long-term, sustainable basis.

Numerous stakeholders are engaged in research and the application of research results to management issues as these relate to different aspects of governance, biological diversity and ecosystem functioning in aquatic, terrestrial, estuarine and marine ecosystems. The experience and opinions of these individuals and organizations represent a vital source of information that was used to shape, test and ratify the WRC's investment strategy in the water environment. To achieve this engagement effectively, a wide range of stakeholders was invited to participate in focused discussion groups. Despite the fact that not all the individuals who were invited could attend these meetings, the project team was able to hold thirteen focus group discussions with 63 selected stakeholders representing 21 different organizations (including research institutes, government departments, universities, NGOs and the private sector) from across the country. The background paper was used to elicit their opinions, concerns and recommendations and to stimulate further debate.

The inputs received from stakeholders, the original WRC outline for this domain, as well as a set of opportunities and constraints derived from a formal process of strategic analysis, formed the basis for the design of three thrusts and their associated programmes for the domain "Water in the Environment". The three thrusts and their programmes are as follows:

Thrust 1: Environmental functioning within the hydrological cycle
Programme 1: Regional and global-scale changes in the (biophysical) environment
Programme 2: Biodiversity
Programme 3: Impacts and management of introduced species
Programme 4: Interfaces
Programme 5: Resource Directed Measures (RDM)
WRC Strategic Issues

Thrust 2: Environmental governance systems
Programme 1: Integrated planning processes
Programme 2: Harmonisation of national governance systems related to water in the environment
Programme 3: Policy Mapping
Programme 4: Regional and global governance systems

Thrust 3: Integrative activities
Programme 1: Communication
Programme 2: Capacity building
Programme 3: Networking
Programme 4: Futures
Programme 5: Strategy maintenance

Thrust 1, the focus of this review, is described in more detail in, MacKay et al., 2004 (WRC Report no KV 148/04).

1.4 Project Level Development for the Thrust "*Environmental Functioning Within the Hydrological Cycle*".

1.4.1 Project objectives

The primary objective of this review is to provide information to support further development and refinement of the investment strategy for the crosscutting domain to project level within the thrust *Environmental Functioning Within the Hydrological Cycle* (Thrust 1). In order to achieve this objective, the following principal tasks were addressed:

1. A thorough review of the national research portfolio (within the WRC and within other institutions and research agencies) related to environmental functioning within the hydrological cycle was conducted. Particular emphasis was paid to the large catchment-scale studies that were conducted from 1975 onwards. Other relevant research was also included. The purpose of the review is two-fold:
    a. To pinpoint and evaluate the extent of our existing knowledge base related to biophysical, biochemical and ecological processes occurring within and between the components of the hydrological cycle (atmospheric, terrestrial, aquatic, subterranean and marine), so as to identify opportunities for high-level integration that could yield substantial new knowledge from relatively low levels of new investment; and
    b. To identify those critical knowledge gaps that preclude a deeper and more complete understanding of processes within the hydrological cycle. Particular importance is attached to the linkages between biophysical components and ecological processes.

2. On the basis of the review of the research portfolio, those projects that would address the strategic needs set out in the scope of the thrust *Environmental Functioning Within the Hydrological Cycle*, and the research programmes within that thrust, were identified, scoped and prioritized.

1.4.2 Approach to the development of a research strategy for Thrust 1

A small team compiled a list of issues based on the development of the thrusts and programmes described in **Section 1.3**, which they believed would be likely to require some level of attention from the Water Research Commission. This would form the major part of the work programme of the domain, and could take the form of:

- Integrating recent WRC research in the field, along with other available information generated from the national research portfolio, and presenting a strategic issues paper that summarizes best available knowledge, sets out the potential implications of current and projected scenarios, and indicates options for policy responses, or areas where policy or research responses will be needed;
- Commissioning highly-focused research projects to integrate and add value to existing knowledge, information and data, and thus deriving new insights to inform and define possible strategic and policy responses; and
- Commissioning or stimulating new basic or applied research where critical gaps in our knowledge around these priority issues are identified.

It is anticipated that this list of priority issues represents a large proportion of the current, emerging or foreseeable issues related to water in the environment that will demand a policy response at the national level in South Africa over the next 3 to 8 years.

A list of priority issues (see **Section 5** for a brief description of each issue), converted into possible titles for issues papers, research projects or even whole research programmes that could be run within one or more of the Key Strategic Areas of the WRC, was sent to a small group of knowledgeable people to obtain their feedback. Each person was asked to comment on the issues presented, identify gaps and to assign a priority to each issue before they were finalized.

1.4.3 Approach to the development of a database

A thorough review of existing research is necessary in order to identify critical knowledge gaps related to environmental functioning within the hydrological cycle. A number of institutions that participate in research within this field were identified as important sources of documented information. For the first phase of the study, the scope of the review was restricted to Water Research Commission publications. The second phase of review focused on appropriate research findings from the Department of Water Affairs & Forestry and the updating of the database with the WRC's current projects and consultancies. It is recognised by the project team that there is a vast array of additional sources of information from other research organisations, tertiary institutions, government departments and private enterprises. It in order to illustrate the additional sources of research outputs that might be relevant to this review, a table listing the organisation/institution and the field/programme of research that was undertaken is presented in **Table 1**. It is important that these sources of information are explored when investigations of existing research for the priority areas of research for this thrust are undertaken as the database does not provide a definitive listing of all the research relevant to the *Environmental Functioning Within the Hydrological Cycle* thrust.

For phase 1, a complete list of publications from the Water Research Commission was analyzed in terms of the scope of the *Environmental Functioning Within the Hydrological Cycle* thrust. Those publications that were considered to be relevant were selected for input into the database. For phase 2 a search of the NISC database was undertaken in order to identify relevant research products to the thrust, these were sourced from the CSIR library, the WRC Archive Library and the DWAF National Library. The results of this search comprised products of which DWAF was the principal institutional author.

The purpose of the database is to provide a brief outline or summary of research undertaken together with a list of referencing details, identification of any relationships between the research and the WRC priority issues, and list the associated components of the hydrological cycle that were studied. The software DBTextWorks was chosen as the preferred database that would be used to store, sort and display the relevant information. An information template was designed to record information for each record; this included: reference details, project details, products linked to the project, project information, level of study, scale of study, location details and keywords.

An example of the information template used to capture information is shown in **Appendix B**. A full list of the keywords used to sort and select appropriate records is shown in **Appendix C**, whilst a

reference user guide to the layout and contents of the database has been prepared as a separate document (see Neal et al., 2004).

Table 1: Listing of institutions and research programmes that have contributed to our understanding of *Environmental Functioning Within the Hydrological Cycle* (that are not included in the review database).

Lead (or Funding) Institution	Research Programme (or Group of Studies)
NRIO	Estuaries of South Africa
Natal Town and Regional Planning	Estuaries of Natal (GW Begg) Wetlands of Natal (GW Begg) Pollution of Natal Rivers (CSIR)
Natal Parks Board	St Lucia system Kosi Bay system
Transvaal Provincial Administration (Nature Conservation Division)	Nylsvlei system Verlorenvlei studies Wakkerstroom studies
FRD (now NRF)	Reservoir programmes: • Hartbeespoort Dam • PK Le Roux Dam • Midmar Dam • Jozini Dam (and Phongolo floodplain system) • Wuras Dam • Hendrik Verowerd Dam (now Gariep Dam) • Transvaal Dams Eutrophication Studies (NIWR) Nylsvlei Programme Lake Sibaya Kosi system Berg River studies (by UCT) Eastern Cape Rivers (Rhodes University and UPE) Red Data Book series Saldanha Lagoon Orange River studies Vaal River studies (eutrophication)
Albany Museum	Fishes in Eastern cape Rivers
Rhodes University	Coastal lakes studies (including Sibaya and Kosi) Knysna – Sedgefield studies Sundays-Fish River transfer studies
CSIR – NIWR - Watertek	Hartbeespoort Dam study 21 Transvaal Impoundments *Microcystis* studies Rietvlei Dam studies Water hyacinth studies Pretoria Salt Pan studies Diatom studies Wetland studies Upper Vaal River studies Natal coastal lakes and Richards Bay Blackfly (*Simulium* spp.) population studies Kruger Park aquatic invertebrate studies Development of SASS methodology Algological studies – rivers and impoundments
ORI	Estuarine studies
UPE	Estuarine studies
UCT	Cape Flats wetlands and vleis

	Desert aquatic ecosystems and ephemeral systems Water quality requirements of aquatic ecosystems
Rhodes University	Eastern Cape Rivers Estuarine studies Fisheries studies
JLB Smith Institute of Ichthyology	Fish studies (rivers, lakes, estuaries)
University of KwaZulu-Natal	Mkuze Swamp studies Midmar Dam studies uMngeni system studies Mangrove studies St Lucia studies Mollusc studies Phongolo floodplain studies
University of Zululand	St Lucia
Wits University	Wetland studies (including Okavango and Nylsvlei) River hydraulics Reedbed studies (natural and man-made) Kruger National Park Rivers Research Programme
Potchefstroom University	Vaal River algal studies Mollusc studies
University of Orange Free State	Pans and ephemeral aquatic systems High altitude aquatic systems in Lesotho
UMngeni Water	uMngeni system studies Water hyacinth control studies

1.5 Purpose and Scope of this Report

This report provides an overview of, and rationale for, the activities that were carried out during phase 1 and 2 of this study. This report is intended to provide WRC research managers with a clear and unambiguous analysis of:

- The extent to which previous research has shaped and defined our understanding of environmental functioning within the hydrological cycle;
- The adequacy or sufficiency of such knowledge for current and future management purposes; and
- The critical knowledge gaps that still need to be addressed in future.

The information presented in this report has been structured into eight sections. The first, introductory section provides a brief overview of, and rationale for, the activities that were carried out during this first phase of study, as well as a description of the activities that were undertaken in the development of a research strategy for thrust 1. The next five sections (Sections 2 to 6) consist of a brief overview and analysis of the all the records that were incorporated into the database and selected graphical representations of the types of information output that can be derived from the database in relation to the components of the hydrological cycle and the Water Research Commission's priority issues for Thrust 1. Sections 7 and 8, respectively, contain a series of discussions and conclusions that have been drawn from the information gleaned during phase 1 and 2 of study. Appropriate appendices provide a detailed analysis of each priority issue for those records where the WRC is the primary institutional author and the status of relevant research pertinent to each issue (**Appendix A**), an example of the information template used to populate the database (**Appendix B**) and a full list of the keywords used to segment and sort the information records (**Appendix C**).

It is important to recognize that this study has focused only on Thrust 1; similar evaluations have been conducted for Thrusts 2 which focuses on *Environmental Governance Systems* (Pegasys, 2005). These

two reviews will feedback into the Domain Water and the Environment's Investment Strategy and will help to determine those research issues that will be prioritised for future investment.

2. ANALYSIS OF DATABASE: AN OVERVIEW

This section provides a brief overview and analysis of the all the records that were incorporated into the database. This includes the WRC records from phase 1, those WRC records that were updated in phase 2 and all the DWAF records from phase 2. It excludes the *current* WRC projects and consultancies that were incorporated into the database in phase 2 (71 records).

The overview of the database analysis is divided into 3 subsections: Section 2.1 refers to the analysis of the WRC records; Section 2.3 describes the analysis of the DWAF records and Section 2.3 refers to a comparative analysis of WRC and DWAF records.

2.1 Analysis of WRC Records

2.1.1 Analysis of WRC Records per Decade

When the database is analysed by the institutional author: WRC, it contains 625 records, out of a total of 1818 published Water Research Commission research reports. This includes phase 1 inputs as well as the records that were included in phase 2 of the study in order to update the database. The number of *current* WRC projects and consultancies that were added in phase 2 of the analysis totals 71 (these are not dated). It is important to note that the subsequent graphs, maps and tables exclude those current records (71 records) and therefore the total number of WRC records analysed is 554.

When this dataset of 554 records is analyzed per decade, for 1970 to 1979; 1980 to 1989; 1990 to 1999 and from 2000 to 2009, it is clear that there has been a steady increase in the numbers of research projects funded by the Water Research Commission that are relevant to the thrust *Environmental Functioning Within the Hydrological Cycle* (**Figure 1**). Here, it is important to remember that the date that was used to analyse the results was the date of publication of the final project report, rather than the date that the research was initiated. Therefore, the lag time between project initiation and completion of the final report needs to be taken into account when describing and evaluating trends in research patterns. Interestingly, no research that was seen as relevant to this thrust was undertaken in the 1970s, and an emphasis on aquatic environmental issues only began to emerge in the mid to late 1980s.

It must be noted that the number of records illustrated from 2005 to 2009 is incomplete (**Figure 1**). All those records from 2005 to 2009 are current projects and consultancies. Only those current projects where information on the project details was available were included in the analysis (Hence the appearance of some records in 2006 and 2008). An additional 71 records are classified as current projects (not dated) but were not included in the analysis since detailed descriptions of the projects were not available and therefore the database fields could not be completed.

Since the number of records does not reflect the investment value made in each project, an analysis of the projects relevant to the thrust *Environmental Functioning Within the Hydrological Cycle* as a proportion of the WRC's total annual research budget should in future be attempted. Financial information is not readily available in a suitable format for analysis and would therefore be time consuming..

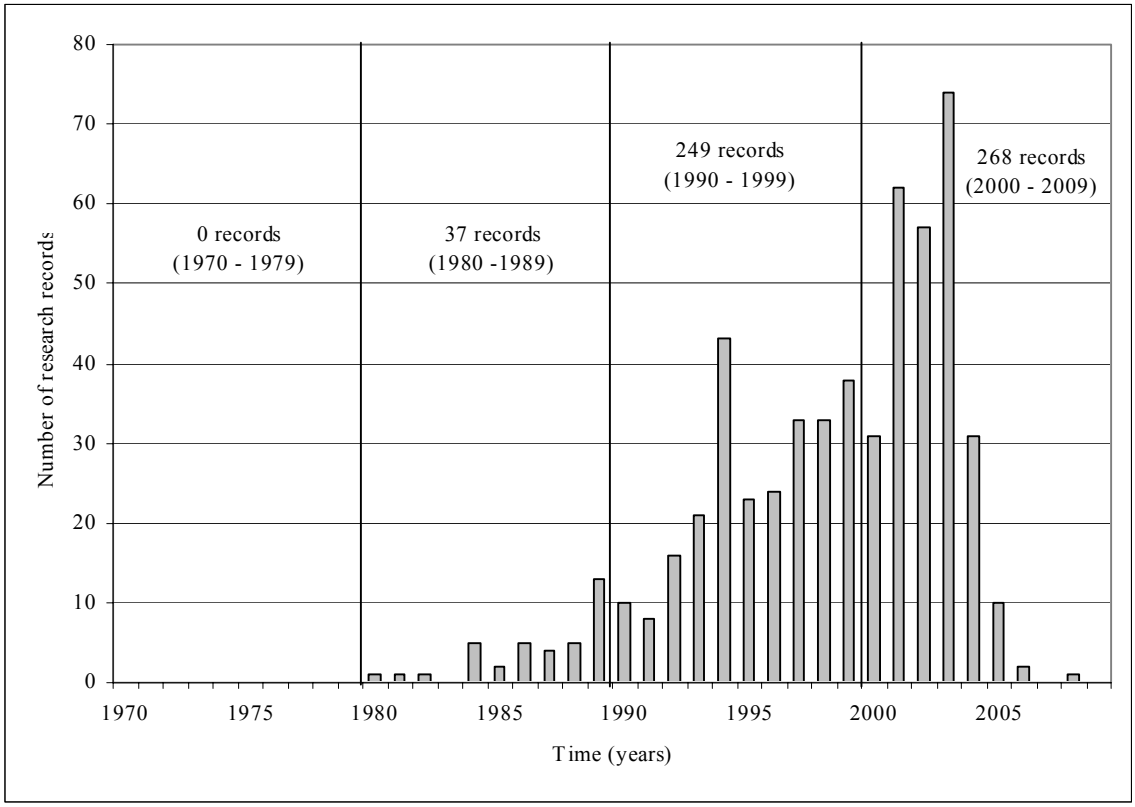

Figure 1: The number of WRC records per decade, from 1970 to 2009 (n=554).

2.1.2 Analysis of the Level of Study

One of the fields of entry within the database was 'level of study'. This criterion allowed differentiation between research that was focused purely on situation assessments (i.e. an inventory or evaluation of the current situation), research that was process-orientated (i.e. that concentrated on specific physical, chemical or biological processes that are or were involved in a given situation), or research that reviewed or supported policy (i.e. research that could provide a firm foundation for the development of appropriate policy instruments, whether or not such instruments were ultimately developed). An examination of the number of records at each of these three levels reveals that most of the research that has been funded by the Water Research Commission has focused on process level issues (**Table 2**). It is important to note that the 'level of study' fields are not mutually exclusive, and in those cases where for example the research was related both to situation assessment and to policy, both of these fields were checked.

Table 2: Number of WRC records per level of study (n = 554).

Level of Study	Number of Records
Situation Assessment	187
Process	385
Policy	32

Importantly, when the numbers of records per decade were combined with an evaluation of the number of records per level of study, this revealed that much of the earlier research funded by the Water Research Commission tended to concentrate on situation assessments; this was followed by a shift in emphasis towards more process-related research (**Figure 2**). Since 1994, policy related research has grown in emphasis and this trend continues to the present time, providing insights into the development of new or modified water resource management policy.

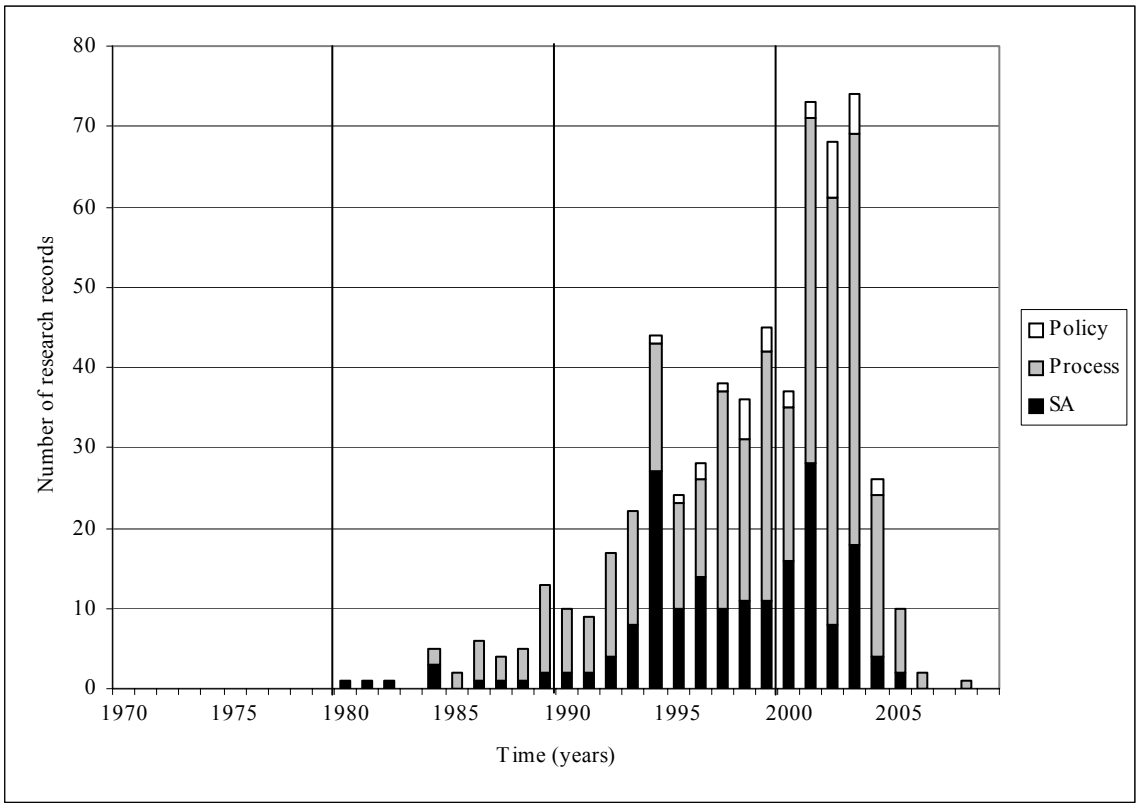

Figure 2: Number of WRC research records per level of study from 1970 to 2009 (n=554).

From the 1980s, there was a rapid increase in the level of attention paid to aquatic ecosystems and their processes, with a particular focus on determinations of the minimum flow requirements needed to sustain ecosystem processes. This research trend was strongly supported by funding from the Water Research Commission and key government departments (DWAF and DEAT), as well as other research-funding organizations. This led to the initiation of comprehensive, multi-disciplinary studies on in-stream flow requirements in rivers and estuaries during the mid-1980s, followed by studies designed to evaluate the implications of integrated environmental management (IEM) principles in 1986. In turn, this triggered the start of larger catchment-scale studies and the intensive syndicated research programme on the Kruger National Park Rivers Research Programme (KNPRRP). This period also marked the start of widespread wetland and estuarine research projects; these were comprised mostly of situation assessments that highlighted areas of concern, helped to define process-related research questions, and identified second-generation research projects. The original financial support from DWAF and DEAT for the syndicated KNPRRP research programme declined during the mid-1990s.

2.1.3 Analysis of the Scale of Study

Another input field in the database was 'scale of study'. This field was divided into five options namely: global, regional (which refers to southern Africa), national (where the study area referred to South Africa), catchment (the study area was confined to a catchment of any scale) and site (the study was site-specific or laboratory based). **Table 3** illustrates the number of records per scale of study. Research carried out at the national level has clearly received the highest priority.

Table 3: Number of WRC records per scale of study (n = 554).

Scale	Number of Records
Global	2
Regional	17
National	240
Catchment	132
Site	163

Examination of the number of research records per decade for each scale of study reveals trends of research projects that operate at a particular scale. This relationship is illustrated in **Figure 3**, where it is evident that the majority of research has been conducted from a national level down to site-specific levels. The number of records at a national level remained more or less constant during the 1990s, whilst the numbers of catchment and site-specific projects fluctuated from year to year. From 2000 to 2003, the number of records at a national scale has doubled, whilst those at catchment scale have remained fairly constant. The number of research projects that are site-specific has increased from eight to an average of 22 projects per year.

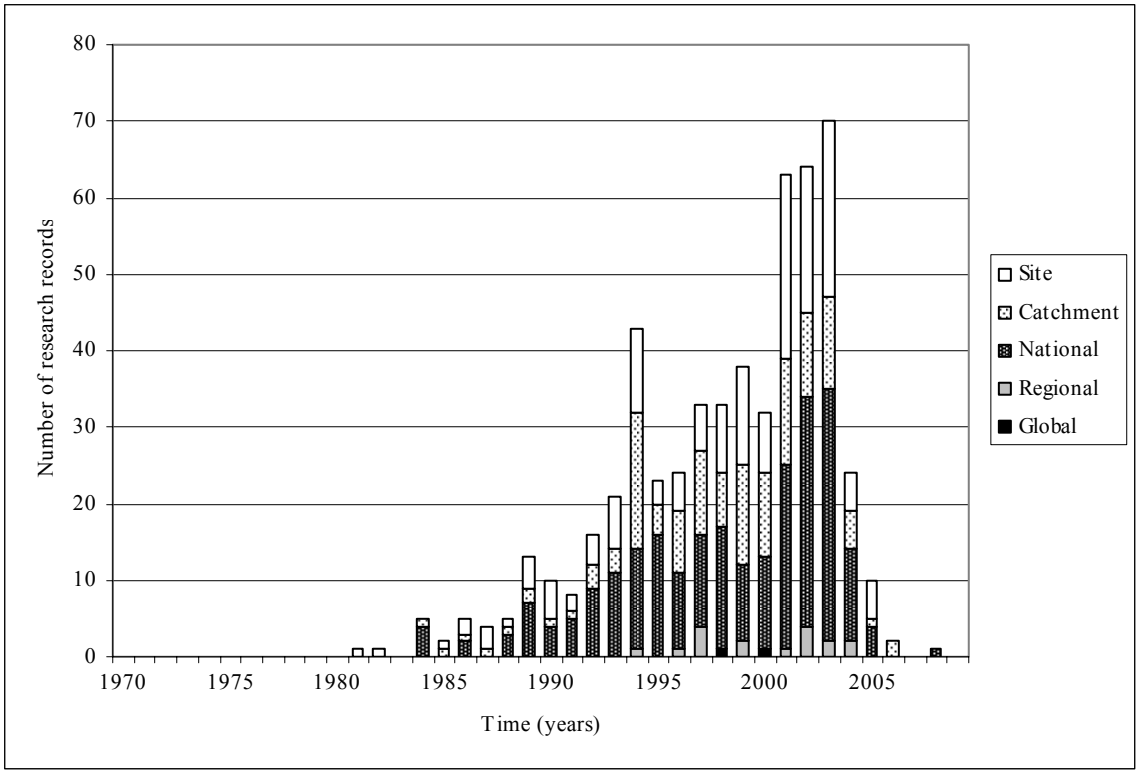

Figure 3: Number of WRC research records per scale of study from 1970 to 2009 (n=554).

2.1.4 Spatial Analysis

The number of research records can be examined in terms of their spatial focus in order to provide some indication of the geographical coverage of the research that has been conducted in South Africa. Only those records that could be assigned to tertiary catchments have been included in the analysis, and a total of 262 research records could be mapped. The 292 studies that were not mapped are categorized in **Table 4**.

The number of projects applicable to each water management area (WMA) is illustrated in **Figure 4**. Clearly, most of the research has been conducted in the Upper Orange and the Inkomati WMAs, with far lower numbers of research projects conducted in the Olifants/Doorn, the Gouritz and the Breede WMAs.

Table 4: Details of WRC research records not included in the spatial analysis

Study Area	Number of research records
Global	2
Regional	17
National	222
Eastern Cape	1
Limpopo	1
KwaZulu – Natal	2
Mpumalanga	1
Northern Cape	2
Western Cape	2
Catchment	11
Laboratory based	1
Unidentified Study Areas	27
Total	**292**

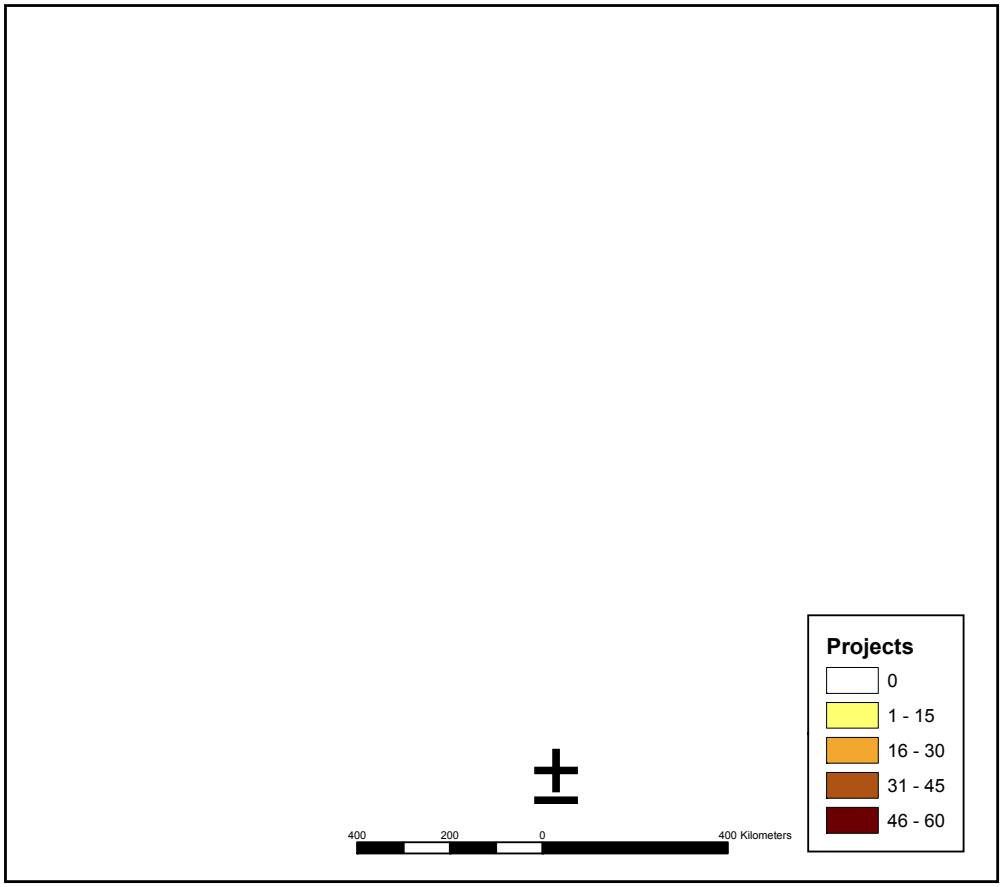

Figure 4: Number of WRC research records per Water Management Area (where 1: Limpopo; 2: Luvuvhu/Letaba; 3: Crocodile (West) and Marico; 4: Olifants; 5: Inkomati; 6: Usutu to Mhlatuze; 7: Thukela; 8: Upper Vaal; 9: Middle Vaal; 10: Lower Vaal; 11: Mvoti to Umzimkulu; 12: Mzimvubu to Keiskamma; 13: Upper Orange; 14: Lower Orange; 15: Fish to Tsitsikamma; 16: Gouritz; 17: Olifants/Doorn; 18: Breede; 19: Berg).

The number of records per primary catchment is illustrated in **Figure 5**. This map shows clearly that most research has been conducted in the central and northern catchments of South Africa, especially the Limpopo (A), Olifants East (B), Vaal (C) and the Crocodile East (X) catchments. A somewhat lower level of research effort has been directed to those catchments comprising the remainder of the Orange River system (D), and then the uMngeni (U) and the Thukela (V) catchments. Those catchments where the least amount of research has been conducted are: the Olifants West (E), Buffels (F), Breë (H), Gourits (J), Kromme (K), Swartkops (M), Sundays (N), Bushmans (P), Great Fish (Q), Keiskamma (R) and the Great Kei (S).

An important insight that can be gained from this analysis is that it appears that the location of many of the research projects are not related specifically to their vicinity to many of the recognized "centres of scientific excellence" located at South African universities (e.g. University of Cape Town, Rhodes University and University of KwaZulu-Natal). Instead, there is some evidence that researchers from these institutions have tended to combine their efforts and focus on key issues of national or regional concern, by conducting collaborative research projects in specific areas. An example of this trend has been the suite of research projects that comprised the Kruger National Park Rivers Research Programme (KNPRRP), where considerable attention was focused on process-orientated research projects.

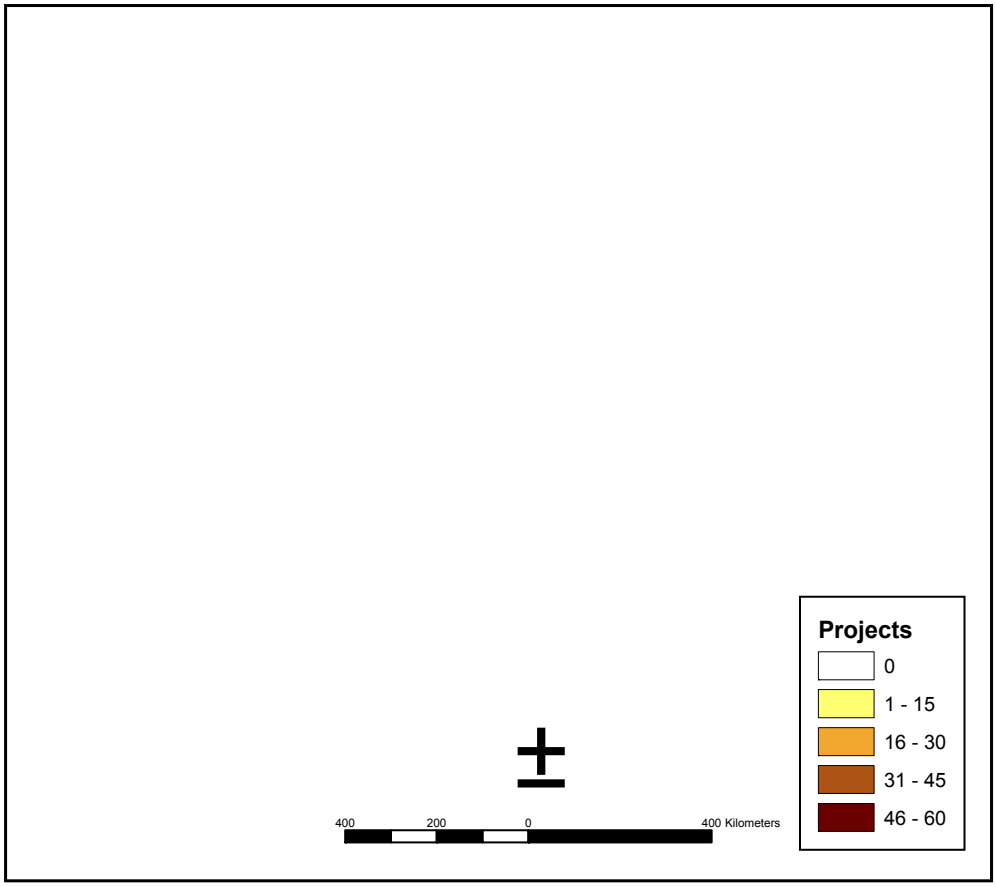

Figure 5: Number of WRC research records per primary catchment (where A: Limpopo; B: Olifants East; C: Vaal; D: Orange; E: Olifants West; F: Buffels; G: Great Berg; H: Breë; J: Gourits; K: Kromme; L: Gamtoos; M: Swartkops; N: Sundays; P: Bushmans; Q: Great Fish; R: Keiskamma; S: Great Kei; T: Mzimvubu; U: uMngeni; V: Thukela; W: Phongolo; X: Crocodile East).

The number of records per tertiary catchment is illustrated in **Figure 6**. Those tertiary catchments that have the highest number of records include those located along the length of the Sabie, Vaal, uMngeni

and Orange rivers. Those catchments with no records are found primarily within Lesotho, and the southern regions of the Upper Vaal and Upper Orange WMAs.

In general, there has been a relatively low level of research coverage for catchments located in the eastern, southern and north-western portions of South Africa. The extensive research conducted on the rivers crossing the Kruger National Park (especially the Sabie River) reflects the more recent emphasis that has been placed on gaining an improved understanding of aquatic ecosystem processes and functioning, through the initiation of research on rivers that South Africa shares with her neighbours. Similarly, the high intensity of research efforts directed to the Orange and Vaal rivers reflects the pivotal role that these two rivers play in South Africa's water resource management plans, and their crucial importance to the country's economy.

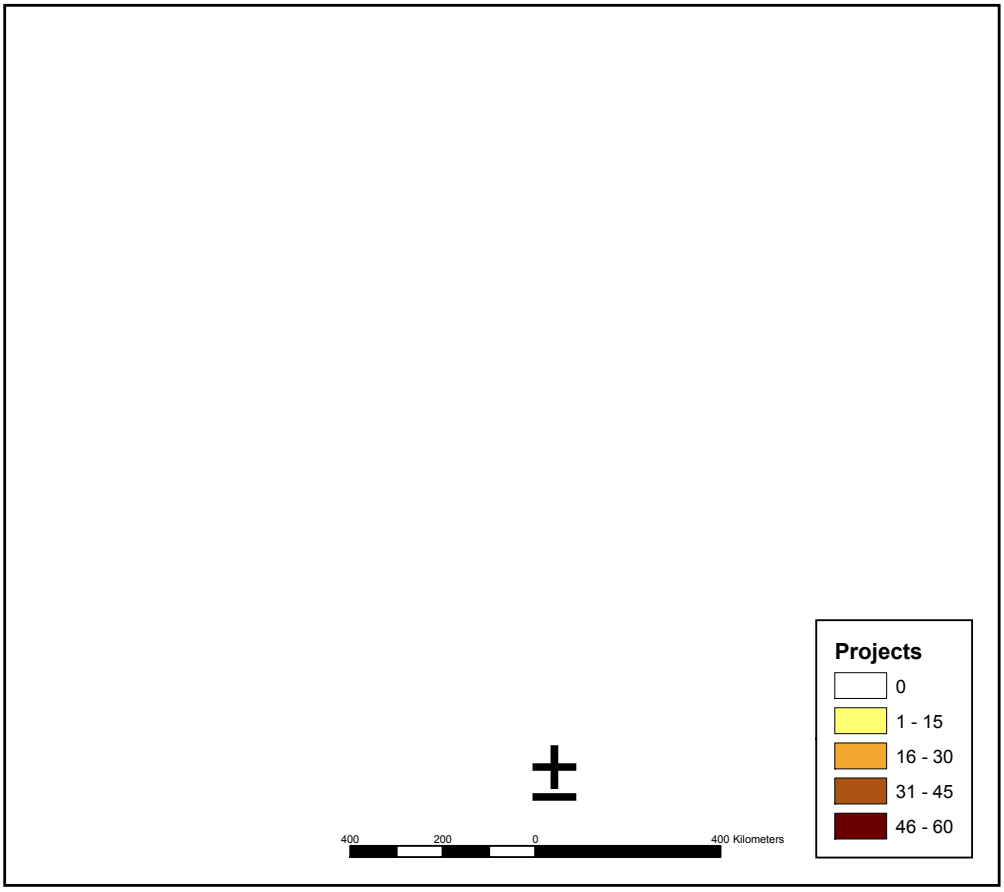

Figure 6: Number of WRC research records per tertiary catchment.

Another perspective from which to analyse the spatial distribution of the research projects funded within the *Environmental Functioning Within the Hydrological Cycle* thrust, is to examine the number of records per tertiary catchment in terms of their distribution in relation to the ecoregions of South Africa (**Figure 7 & Figure 8**). Level 1 ecoregions for South Africa were derived from terrain and vegetation data, with some consideration of altitude, rainfall, runoff variability, air temperature, geology and soils (DWAF, 2003). Those ecoregions with the most records (between 30 and 60 records) include the Lowveld; North Eastern Highlands; Highveld; Eastern Escarpment Mountains; Nama Karoo; and the Orange River Gorge. Clearly, there are several sections within the Highveld and Eastern Escarpment Mountains ecoregions where no research has been conducted. This could represent an important information gap in the national research effort, and this should be evaluated in more detail in the next phase of this project. It is also important to note that the intense level of research attention focussed along the Sabie, Vaal and Orange rivers is not necessarily equally applicable to the entire ecoregion centred on the respective river systems.

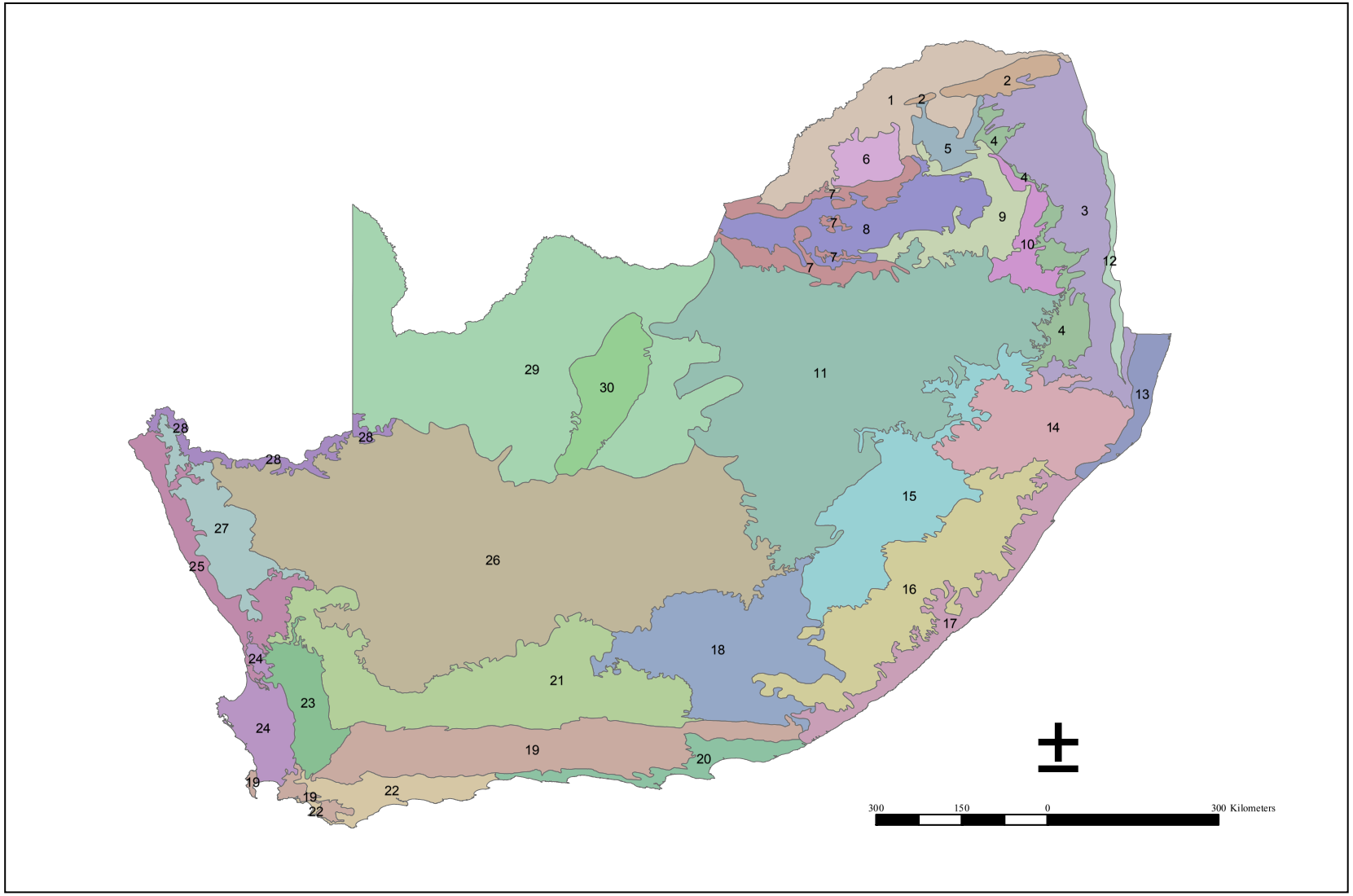

Figure 7: Level 1 Ecoregions of South Africa (see Figure 8 for legend explanation; Map sourced from DWAF, 2003).

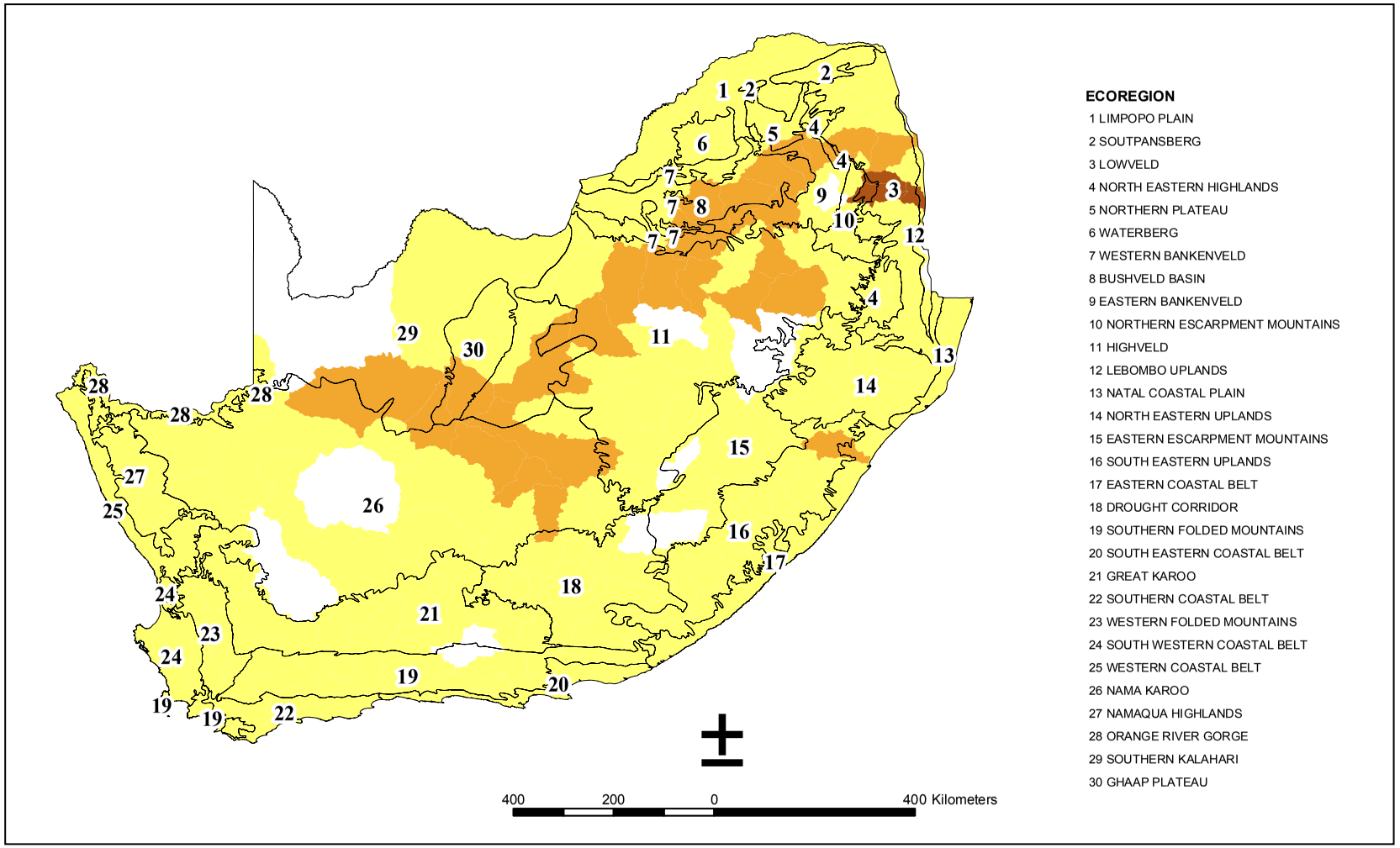

Figure 8: Level 1 Ecoregions of South Africa overlaid by number of WRC research records per tertiary catchment (see Figure 7; Map sourced from DWAF, 2003).

2.2 Analysis of DWAF Records

2.2.1 Analysis of DWAF Records per Decade

When the database is analysed by the institutional author: DWAF, it contains 230 records. When this dataset is analyzed per decade, for 1970 to 1979; 1980 to 1989; 1990 to 1999 and from 2000 to 2009, it is evident that DWAF-funded research that is relevant to the thrust *Environmental Functioning Within the Hydrological Cycle* was largely undertaken in the 1970s and 1980s (**Figure 9**).

The temporal spread of projects and studies that DWAF commissioned or conducted was strongly influenced by the specific water resource management information needs that prevailed at the time. In particular, these information needs centred on a requirement to quantify and understand the factors affecting the availability of water resources within specific catchments and the prevailing and anticipated future demands for water that would be made on these resources. These studies provided the basis for DWAF decisions on the selection and prioritization of management options to meet the most pressing water needs, identified those catchments whose rivers had been most severely affected by specific water quality problems, and formed the basis for a broad-scale understanding of the water needs of aquatic ecosystems.

The last decade in the graph, 2000 to 2009, has been included for consistency in reporting and is an artefact from the Figure 1 where 2005 to 2009 illustrates records that the DWAF initiated in this decade which is not complete and therefore the number of records in this decade is not a true reflection of the total number of research projects that DWAF will fund or undertake in this time period in the future.

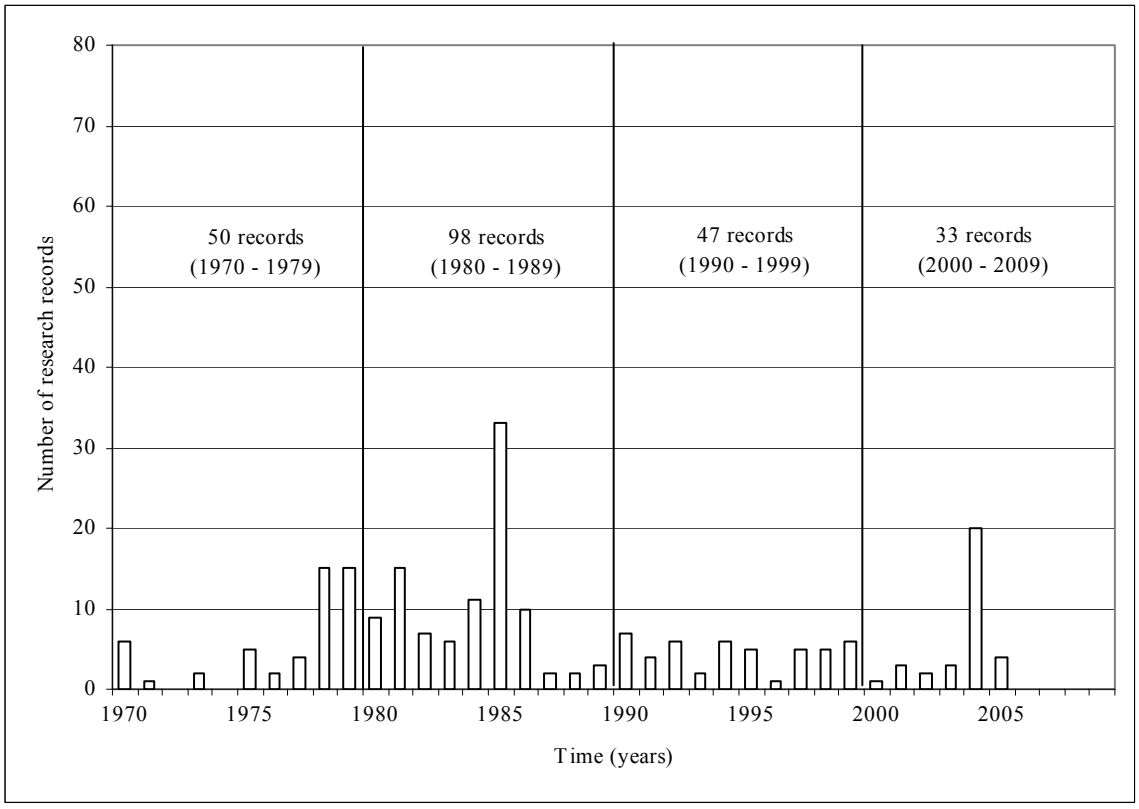

Figure 9: The number of DWAF records per decade, from 1970 to 2009 (n=230; 2 records were undated).

Please note: the date that was used to analyse the results was the date of publication of the report, not the date that the research was initiated.

2.2.2 Analysis of the Level of Study

One of the fields of entry within the database was 'level of study'. This criterion allowed differentiation between research that was focused purely on situation assessments (i.e. an inventory or evaluation of the current situation), research that was process-orientated (i.e. that concentrated on specific physical, chemical or biological processes that are or were involved in a given situation), or research that reviewed or supported policy (i.e. research that could provide a firm foundation for the development of appropriate policy instruments, whether or not such instruments were ultimately developed). The number of records at each of the three levels of study is displayed in **Table 5**. It is evident that the majority of the research undertaken is at the situation assessment level. This strong emphasis on situation assessments was based on DWAF's need to obtain detailed information on the availability of water and the competing demands for water within key catchments. The process-related studies focussed on specific water quality problems - especially eutrophication, salinisation and contamination by heavy metals and bacteria – for key river systems that provided water for a variety of human uses.

Table 5: Number of DWAF records per level of study.

Level of Study	Number of Records
Situation Assessment	158
Process	64
Policy	8

When the numbers of records per decade were combined with an evaluation of the number of records per level of study, this revealed that in the 1970s and 1980s most of the research concentrated on a mix of situation assessments and process-related research; this was followed by a shift in emphasis towards more situation assessment dominated research in the 1990s to present (**Figure 10**). The majority of the process-related studies that DWAF commissioned during the 1970s and 1980s were focussed primarily on the causes and consequences of eutrophication and salinisation in key river systems. These studies provided the basis for decisions on the allowable limits of various compounds in effluent discharge streams and results formed the scientific basis for statutory limits designed to control water quality problems, especially the 1 mg/litre effluent phosphorus standard.

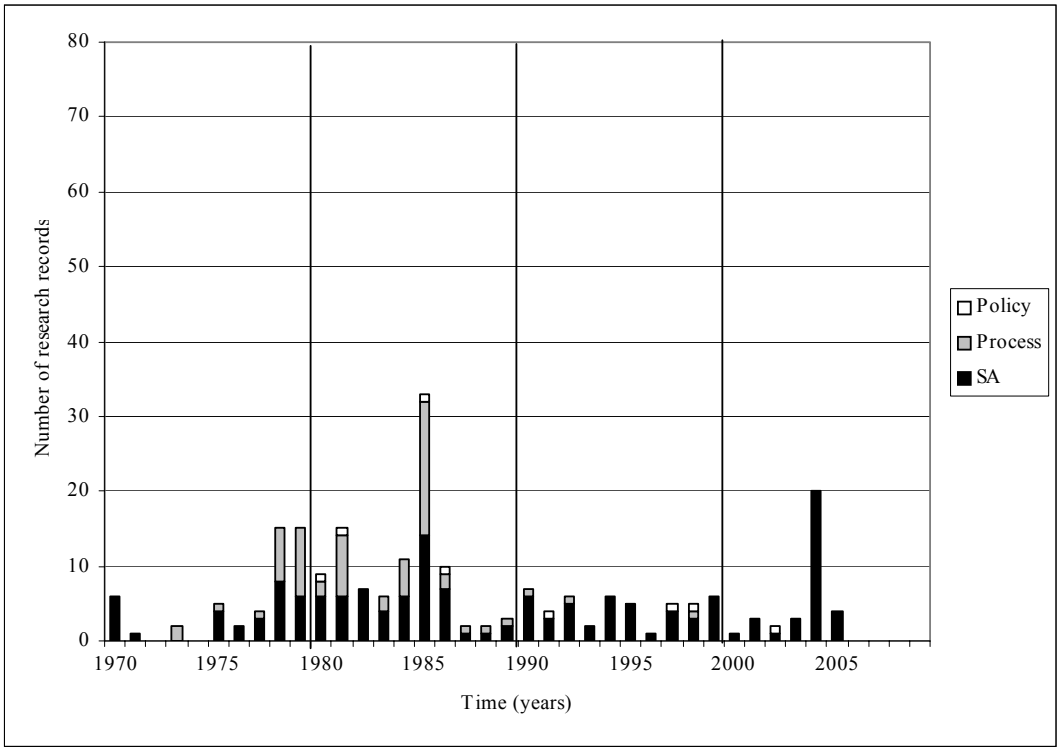

Figure 10: Number of DWAF research records per level of study from 1970 to 2009 (n=230).

2.2.3 Analysis of the Scale of Study

The 'scale of study' field in the database is divided into five options namely: global, regional (which refers to southern Africa), national (where the study area referred to South Africa), catchment (the study area was confined to a catchment of any scale) and site (the study was site-specific or laboratory based). **Table 6** illustrates the number of records per scale of study. Research carried out at the catchment and national level has received the highest priority.

Table 6: Number of DWAF records per scale of study.

Scale	Number of Records
Global	0
Regional	10
National	80
Catchment	88
Site	52

At the site level of analysis, 2 records were at a provincial level; one was laboratory-based and the balance focussed on specific sites, primarily dam studies.

Examination of the number of research records per decade for each scale of study is illustrated in **Figure 11**. During the 1970s and 1980s the majority of the research was at a national scale, while in the 1990s and 2000s catchment scale research became more dominant.

The emphasis on national, catchment and site levels of study is entirely appropriate for a national government department. In addition, the few regional scale studies consisted of similar work conducted in catchments linked to river systems that South Africa shares with its neighbours. From the mid-1980s, most of the research related to aquatic ecosystems was conducted by other organizations, with very few projects being commissioned by DWAF.

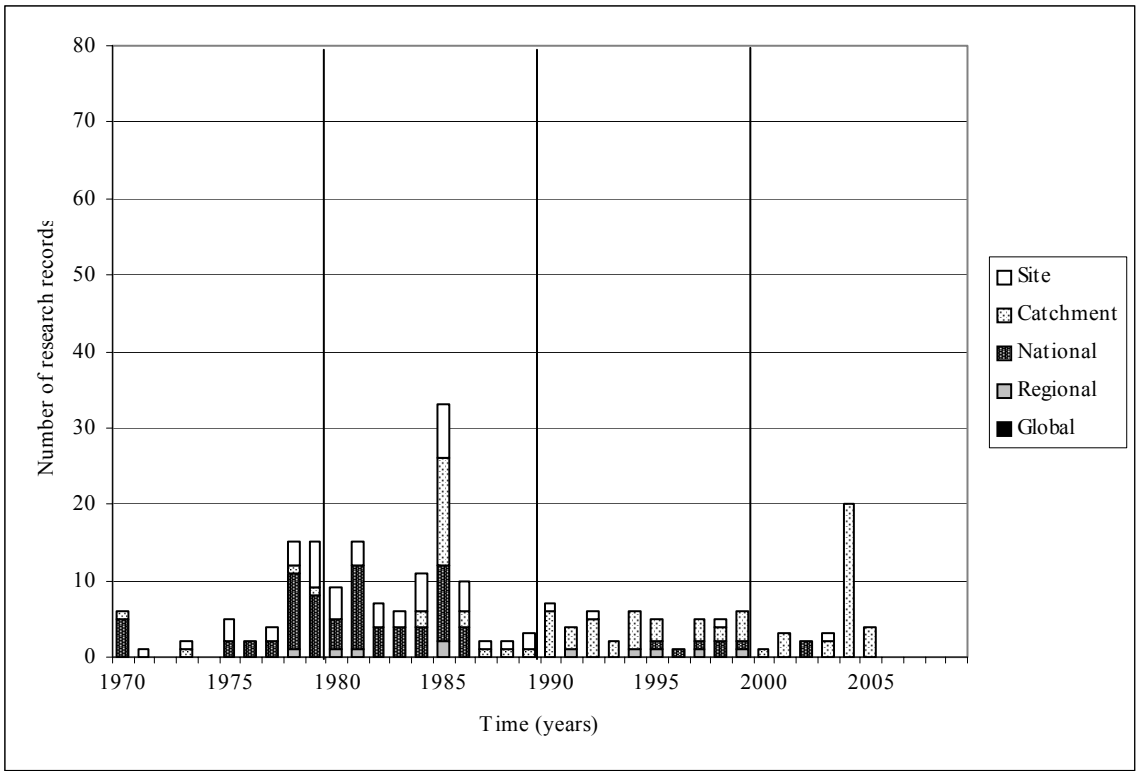

Figure 11: Number of DWAF research records per scale of study from 1970 to 2009 (n=230).

2.3 Combined Analysis of WRC and DWAF Records

2.3.1 Analysis of WRC and DWAF Records per Decade

When the WRC and DWAF records are combined, it is interesting to note from the decadal analysis for the period 1970 to 2009, that there has been a steady increase in the numbers of research projects undertaken that are relevant to the thrust *Environmental Functioning Within the Hydrological Cycle* (**Figure 12**).

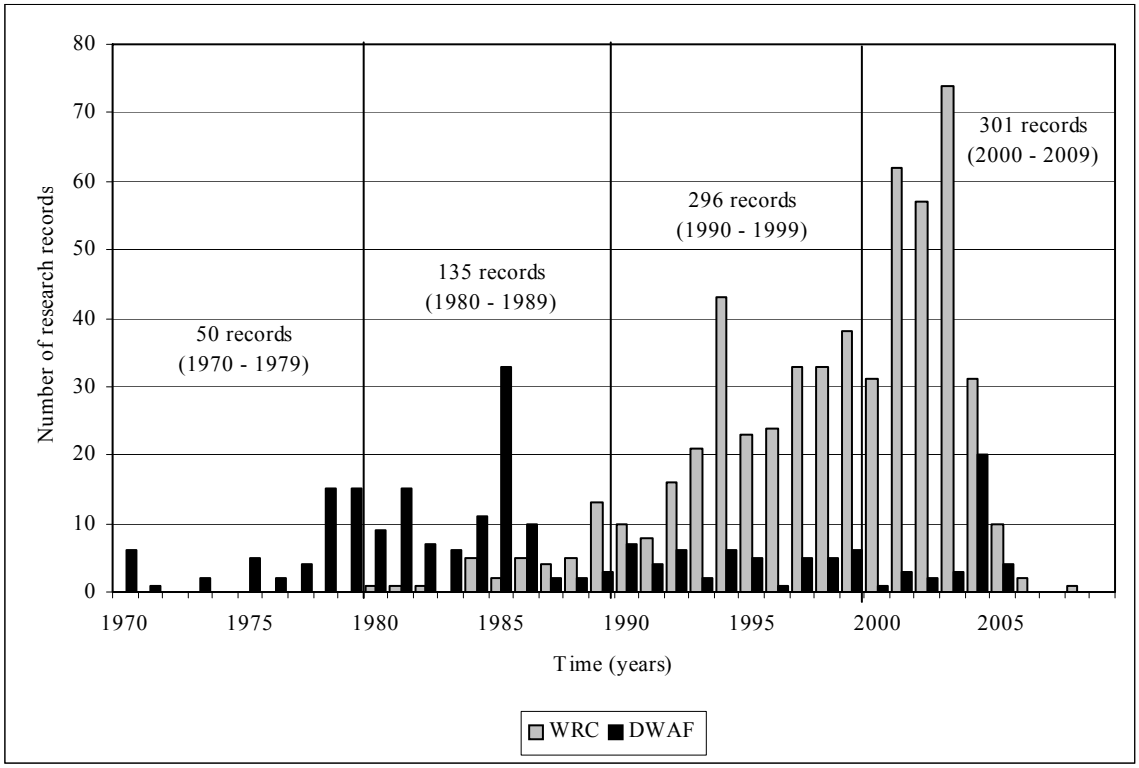

Figure 12: The number of WRC and DWAF records per decade, from 1970 to 2009 (n=782).

The number of aquatic ecosystem studies commissioned by DWAF declined sharply during the mid-1980s and this decade also marks the sharp increase in such studies commissioned by the WRC. This transition represents an acceptance by WRC that such studies were more closely aligned to its mandate than to the DWAF. The ecological studies commissioned by DWAF since 1990 represent the series of projects aimed at determining in-stream flow requirements in specific river systems, followed by more closely focussed research aimed at determining the water requirements of the ecological reserve in specific river systems. The research projects commissioned by the WRC addressed a far broader spectrum of issues related to the ecological aspects of the hydrological cycle, but were also closely linked to the specific information needs of DWAF.

2.3.2 Analysis of the Level of Study

Overall the majority of the records were aimed at process level research (449 records; **Table 7**). It is apparent that the WRC focused mainly on process level research, while the DWAF focused on situation assessments. This comparison highlights the important role of the WRC in providing both situation assessment and process-related information, with some information provided to assist with policy formulation. This contrasts with DWAF's focus on obtaining catchment-specific situation assessment information and process-related information designed to inform specific management choices.

Table 7: Number of WRC and DWAF records per level of study.

Level of Study	Number of WRC Records	Number of DWAF Records	Total Number of records
Situation Assessment	187	158	345
Process	385	64	449
Policy	32	8	40

2.3.3 Analysis of the Scale of Study

Research that is applicable at the national scale dominates the numbers of research projects funded by WRC, though catchment-scale and site-specific scales are also important (**Table 8**). Relatively few WRC studies were considered to have regional or global applications. This trend is quite similar to that shown for the numbers of studies commissioned by DWAF, where national, catchment and site-specific scales dominated. This geographical spread of research effort is entirely consistent with the mandates of these two organizations, though there is a growing need to provide more information that is relevant at a regional (i.e. SADC) scale.

Table 8: Number of WRC and DWAF records per scale of study.

Scale	Number of WRC Records	Number of DWAF Records	Total Number of records
Global	2	0	2
Regional	17	10	27
National	240	80	320
Catchment	132	88	220
Site	163	52	215

3. ANALYSIS OF DATABASE FROM A HYDROLOGICAL CYCLE COMPONENT PERSPECTIVE

Water appears in various forms as a component of all aspects of the environment, reflecting the different phases of the hydrological cycle. **Figure 13** presents a simplified representation of the hydrological cycle in its different components (atmospheric, marine, aquatic, terrestrial and subterranean), to illustrate that all water resources are linked to, and exert direct and indirect effects on, the broader environment, via water itself.

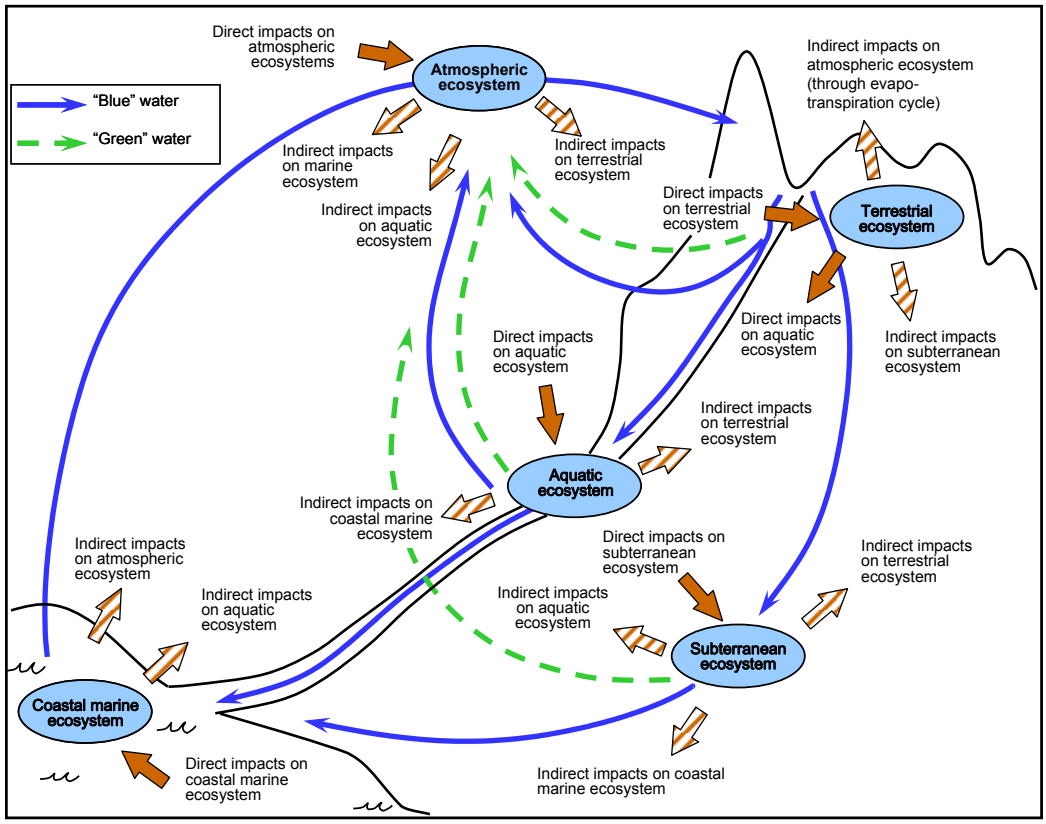

Figure 13: Components of the hydrological cycle.

In order to categorise the database records in terms of their relationship to the components of the hydrological cycle, the database incorporated an input data field for each hydrological cycle component. When determining which hydrological cycle component that a study focused on, the following broad definitions were used. The "aquatic" component included all studies related to surface water, and included wetlands and estuaries; the "atmospheric" component included all processes that occur in the atmosphere, e.g. evaporation and cloud seeding; the "terrestrial" component included all research that was primarily focused on terrestrial issues such as water treatment plants, mining rehabilitation and soil-water studies; the "subterranean" component included studies such as borehole analysis, aquifers, groundwater processes and groundwater dependent ecosystems; and the "marine" component focused primarily on near-shore marine, as well as sea and ocean studies, including ocean currents and marine outfalls used for effluent discharge.

The section is divided into 3 subsections: Section 3.1 refers to the analysis of the WRC records; Section 3.3 describes the analysis of the DWAF records and Section 3.3 refers to a comparative analysis of WRC and DWAF records.

3.1 Analysis of WRC Records

The number of records per hydrological cycle component for those records where WRC is the institutional author is summarized in **Table 9.**

Table 9: Number of WRC research records per hydrological cycle component.

Hydrological Cycle Component	Number of Records
Aquatic	283
Atmospheric	42
Marine	8
Subterranean	103
Terrestrial	118
Total	**554**

Here, it is important to note that almost all research into the different aspects of the marine component falls outside the primary mandate of the Water Research Commission. However, whilst the Water Research Commission has not funded research projects on this component, other agencies and institutions have supported such research.

A temporal analysis of the number of records per decade for each hydrological cycle component is illustrated in **Figure 14.** As can be seen from this figure, the primary focal area for investment by the Water Research Commission has been on the aquatic component of the hydrological cycle, reflecting the core mission of the Water Research Commission. In the 1990s, research on the terrestrial component received more attention than in the 1980s, and this component has also received increased emphasis in the period 2000 to 2004. Consideration of the subterranean component of the hydrological cycle increased significantly from 2 projects in 1990 to 19 in 2004. It must be borne in mind when interpreting the trends in **Figure 14,** that the allocation of hydrological cycle component to a record was based on the primary focus of each project; many of the research projects undertaken to date have addressed more than one component of the hydrological cycle at a secondary level of detail.

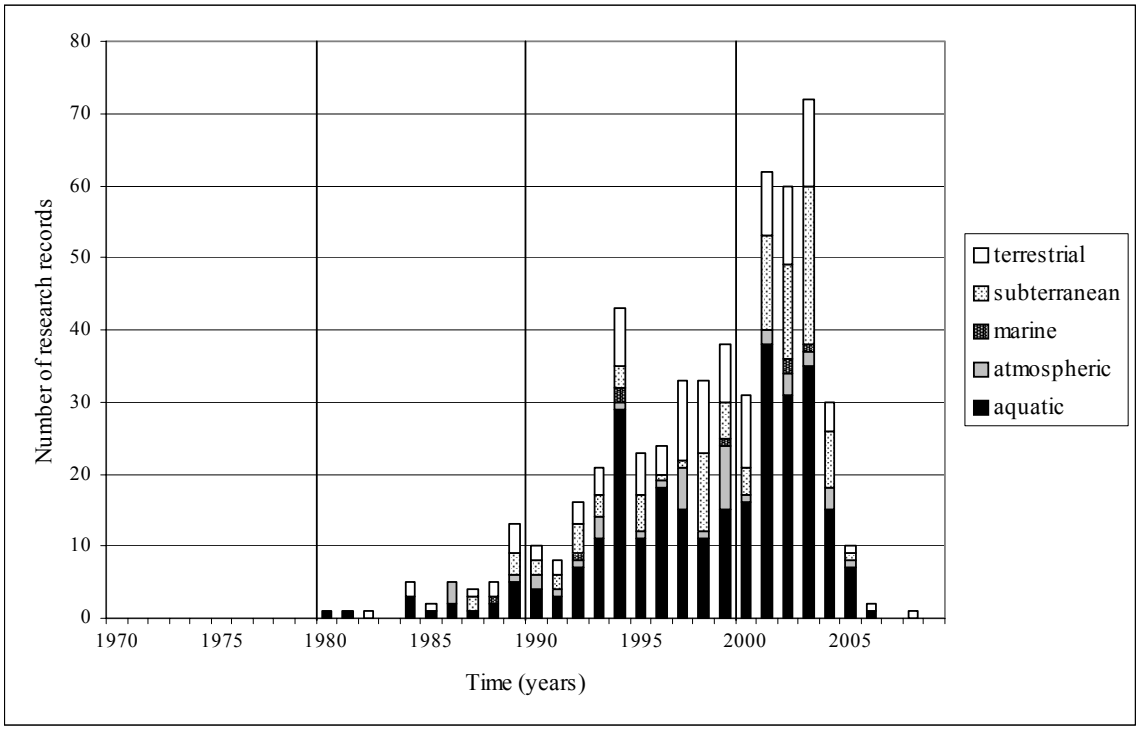

Figure 14: Number of WRC research records per hydrological cycle component from 1970 to 2009 (n = 554).

Research projects that have focused on estuarine studies can be separated from those research records that are classified as comprising the aquatic component of the hydrological cycle. The temporal distribution of these records is shown in **Figure 15**. The separation of research records for the aquatic and estuarine components of the hydrological cycle demonstrates that support for estuarine research projects has only been initiated relatively recently and reflects the growing importance attached to this component. It is difficult to make a meaningful comparison of the relative numbers of research records for these two components, since each has received dramatically different levels of research support.

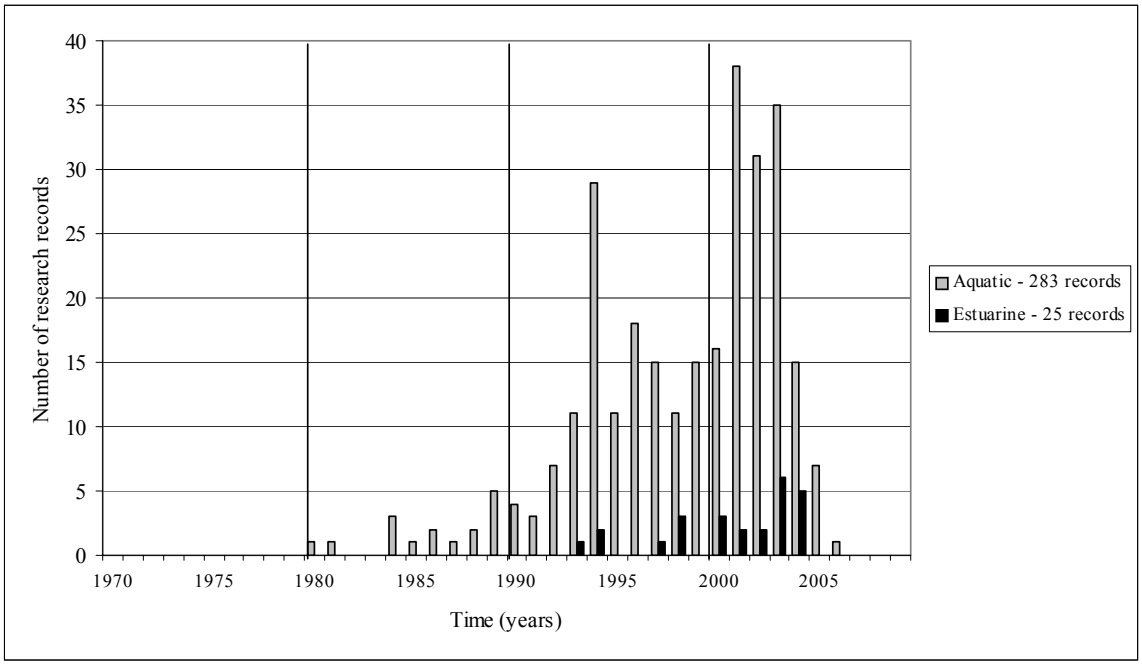

Figure 15: Comparison of the temporal distribution of the numbers of WRC research records that focused on estuarine research, with the numbers of research records that focused on the aquatic component of the hydrological cycle, from 1970 to 2009.

When analysing the research conducted on hydrological cycle components according to the type or level of study carried out, it is apparent that for all components the primary focus has been on process-orientated research (**Table 10**). Relatively little policy-related research has been conducted and this has been undertaken primarily on the aquatic component.

Table 10: Number of WRC records of each hydrological cycle component per level of study (n = 554).

	Situation Assessment	**Process**	**Policy**
Aquatic	110	182	25
Atmospheric	4	38	0
Marine	2	6	0
Subterranean	42	64	3
Terrestrial	29	95	4

At a global and regional scale, some research has focused on the atmospheric and marine components of the hydrological cycle, whilst the aquatic component has received the most attention at national, catchment and site-specific scales. Research studies on the subterranean component of the hydrological cycle have been conducted primarily at a site-specific scale, whilst most terrestrial research has been conducted at a national scale (**Figure 16**).

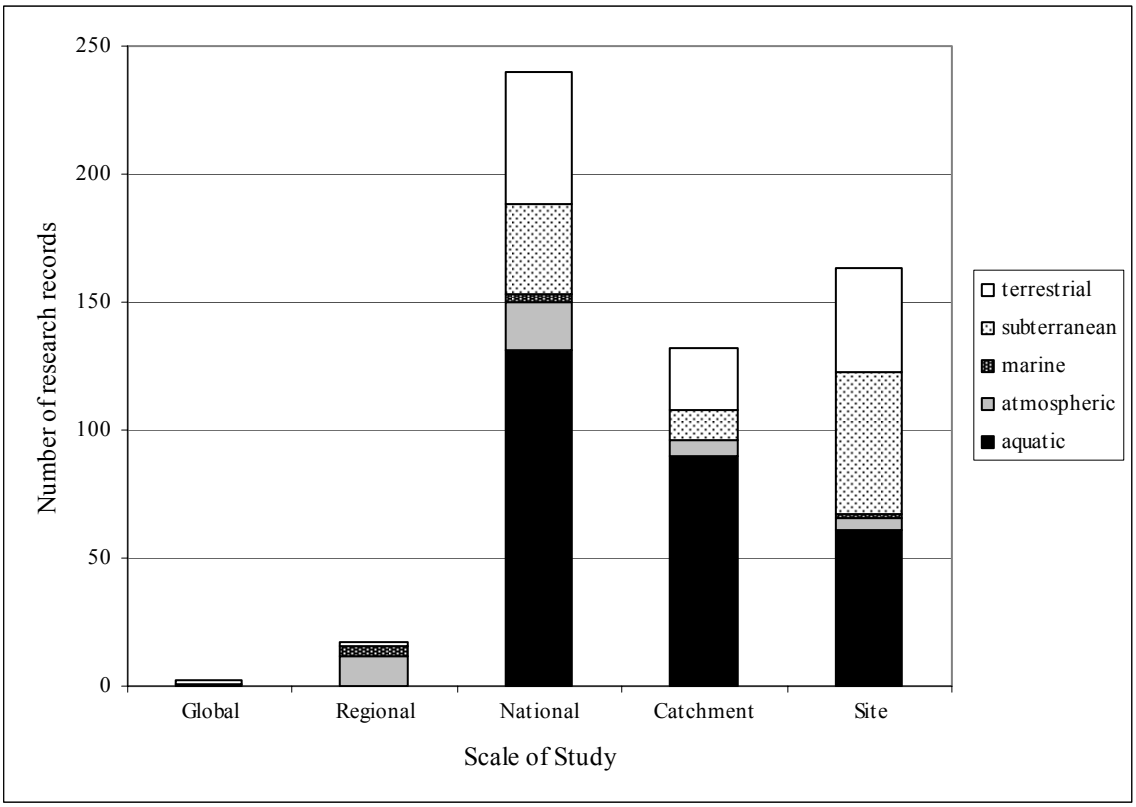

Figure 16: Number of WRC research records for each hydrological cycle component per scale of study (n = 554).

Another important point to remember is that almost all organizations that fund research are reluctant to fund syndicated research programmes where their individual participation, or the component funded by them, may be difficult to distinguish from the contributions made by other funding agencies. This has limited Water Research Commission support for syndicated research at global scale, as well as at regional and national scales. Instead, the Water Research Commission focus has been to fund discrete research projects that have clearly defined activities and outputs.

3.2 Analysis of DWAF Records

The number of research records per hydrological cycle component for those records where DWAF is the institutional author is summarized in **Table 11.**

Table 11: Number of DWAF research records per hydrological cycle component.

Hydrological Cycle Component	Number of Records
Aquatic	187
Atmospheric	7
Marine	0
Subterranean	18
Terrestrial	18
Total	**230**

The majority of the records fall within the aquatic component of the hydrological cycle; this is expected since this reflects the core mandate of the DWAF. The marine component received no support from DWAF; again this is expected since marine research falls outside the primary focus area of DWAF.

When the number of records is examined per decade for each hydrological cycle component (**Figure 17**), it is clear that the core area of research for DWAF is the aquatic component. In the late 1970s to mid 1980s, the terrestrial, atmospheric and subterranean components began to receive more attention. This trend however did not continue into the 1990s and 2000s, where research on the aquatic component dominated. Once again, this is entirely aligned with DWAF's core mandate to focus on surface water aquatic systems. The relatively modest emphasis on ecological processes within subterranean or terrestrial systems during the 1970s and 1980s reflects the specific needs to understand the basic processes and quantities of water needed by the systems. Later research in these specific arenas has been funded by other institutions.

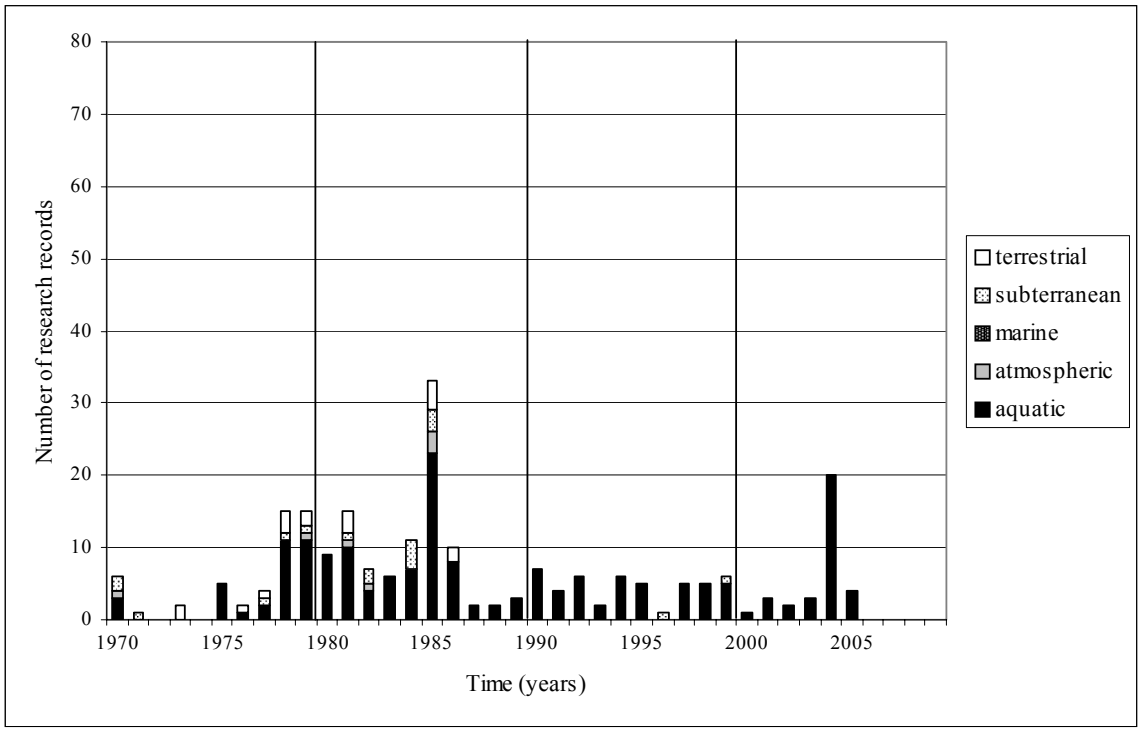

Figure 17: Number of DWAF research records per hydrological cycle component from 1970 to 2009 (n = 230).

When analysing the research conducted on the hydrological cycle components according to the level of study, it is evident that the majority of the research undertaken was at a situation assessment level for the aquatic component of the hydrological cycle. Process level research within the aquatic component is also relevant within DWAF with 45 records in this category (**Table 12**). The only research in support of, or in response to, policy occurs within the aquatic component. It must be realised, however that policy level research does not include legislation, regulations and guidelines that are developed by DWAF.

Table 12: Number of DWAF records of each hydrological cycle component per level of study.

	Situation Assessment	**Process**	**Policy**
Aquatic	134	45	8
Atmospheric	5	2	0
Marine	0	0	0
Subterranean	13	5	0
Terrestrial	6	12	0

No DWAF research has been conducted at a global scale while very few research projects have been undertaken at a regional scale (**Figure 18**). At the national, catchment and site-specific scales, research has been concentrated on the aquatic component of the hydrological cycle. Terrestrial studies at a national level and subterranean studies at a national and site-specific scale have received modest levels of attention.

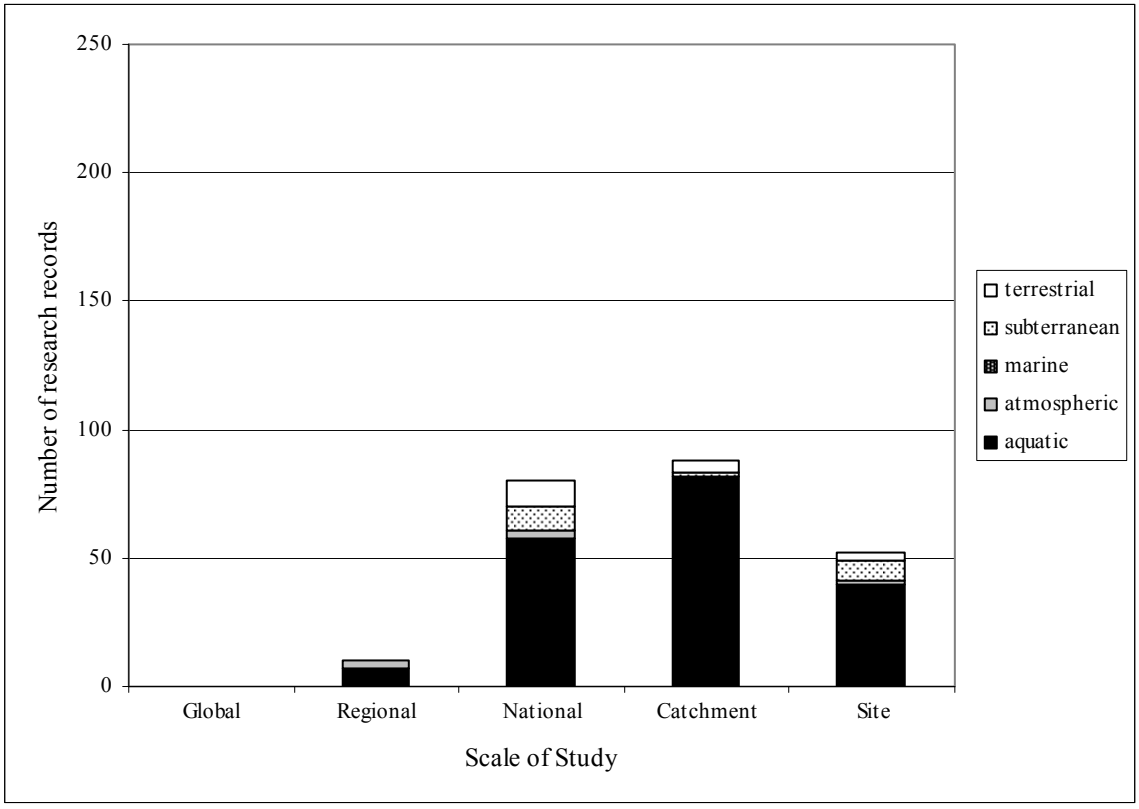

Figure 18: Number of DWAF research records for each hydrological cycle component per scale of study (n = 230).

3.3 Combined Analysis of WRC and DWAF Records

It is expected that the main focus areas of the research conducted or commissioned by both WRC and DWAF is within the aquatic component of the hydrological cycle (**Table 13**) since this is their core mandate. However, it is encouraging to note that the two organizations are able to cover all components of the hydrological cycle between them. The terrestrial and subterranean components are receiving increasing attention, and this is an indication of increasing recognition that water resource management has to be holistic and needs to take cognisance of all aspects of the hydrological cycle. The marine component has received the least attention; however research in this field is funded and undertaken by other organisations.

Table 13: Number of WRC and DWAF research records per hydrological cycle component.

Hydrological Cycle Component	Number of WRC Records	Number of DWAF Records	Total Number of Records
Aquatic	283	187	470
Atmospheric	42	7	49
Marine	8	0	8
Subterranean	103	18	121
Terrestrial	118	18	136

4. DETAILED ANALYSIS OF HYDROLOGICAL CYCLE COMPONENTS

This section describes in detail with number of records within each of the components of the hydrological cycle that have been commissioned by the WRC (Section 4.1) and by DWAF (Section 4.2).

4.1 Analysis of WRC Records

4.1.1 Aquatic

Figure 19 illustrates the number of records that have been classified as comprising the aquatic component of the hydrological cycle per tertiary catchment. Some tertiary catchments located along the Sabie, Olifants, Orange and Vaal rivers have the highest levels of research coverage, while little or no research has been conducted in the northern and southern regions of the Lower Orange WMA, and the northern regions of the Lower Vaal WMA, and in Lesotho.

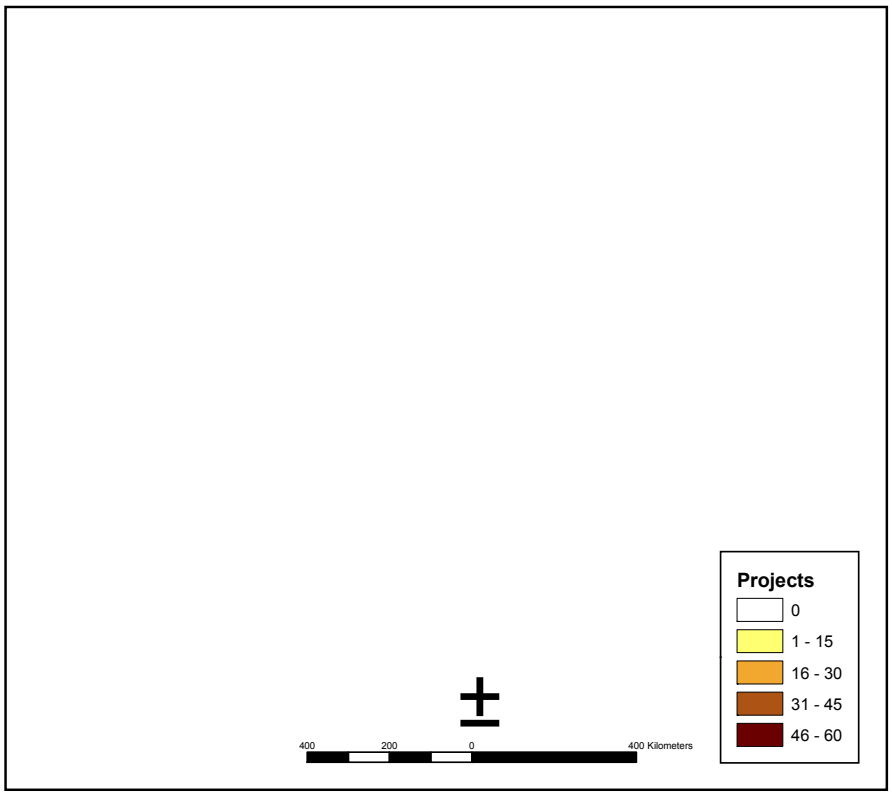

Figure 19: Number of WRC research records per tertiary catchment within the aquatic component of the hydrological cycle (n=282).

Figure 20 illustrates the relationship between the number of records classified as addressing the aquatic component, and the scale and level of the study. It is evident that the majority of the records are at the national scale and consist primarily of situation assessment and process orientated projects. Not unexpectedly, most of the policy-related research has been conducted at a national scale, rather than catchment or site-specific scales. At the site-specific scale, the primary focus has been process level research. Little to no research has been conducted at the global and regional scales for the aquatic component of the hydrological cycle.

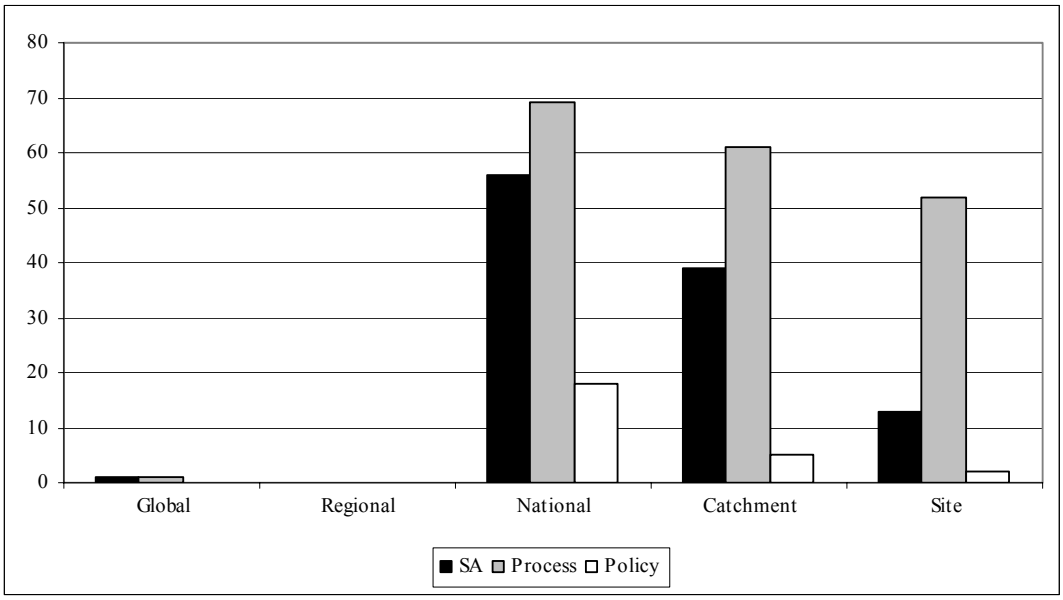

Figure 20: Number of WRC research records per scale and per level within the aquatic component of the hydrological cycle (n=317).

4.1.2 Marine

Very little of the research funded by the WRC has had a purely marine focus (**Figure 21**), and most of the research that has been undertaken cannot be displayed in **Figure 21** because the projects could not be allocated to a tertiary catchment. Those studies that are illustrated focus on marine outfalls and marine pollution and waste disposal research projects that are linked to various site-specific harbours and bays.

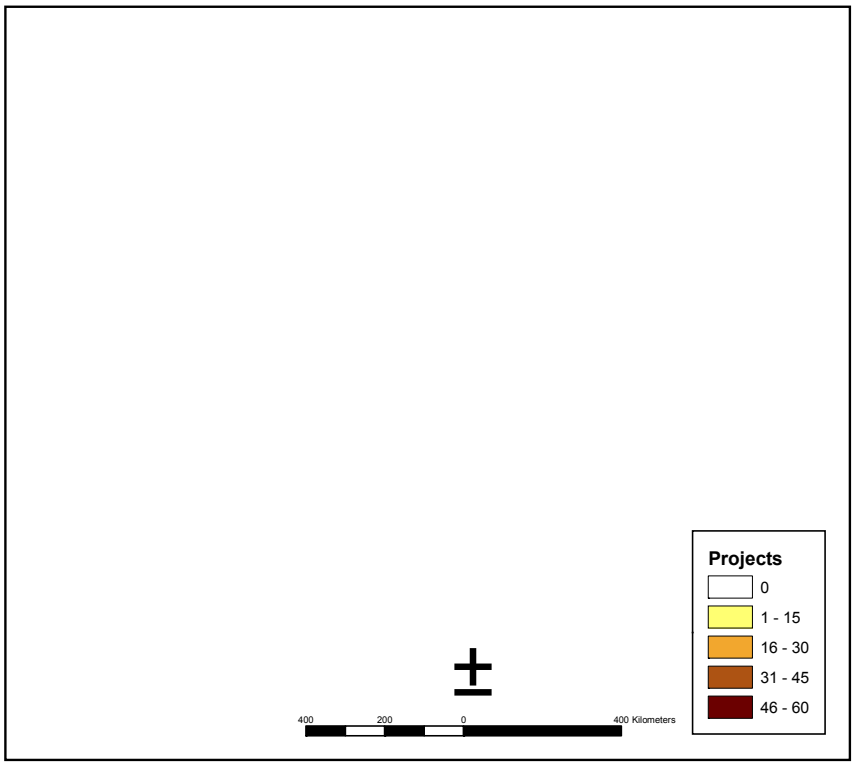

Figure 21: Number of WRC research records per tertiary catchment within the marine component of the hydrological cycle (n=9).

The majority of the marine research has application at both regional and national scales (**Figure 22**). These studies focus primarily on ocean currents and their behaviour as it relates to weather patterns.

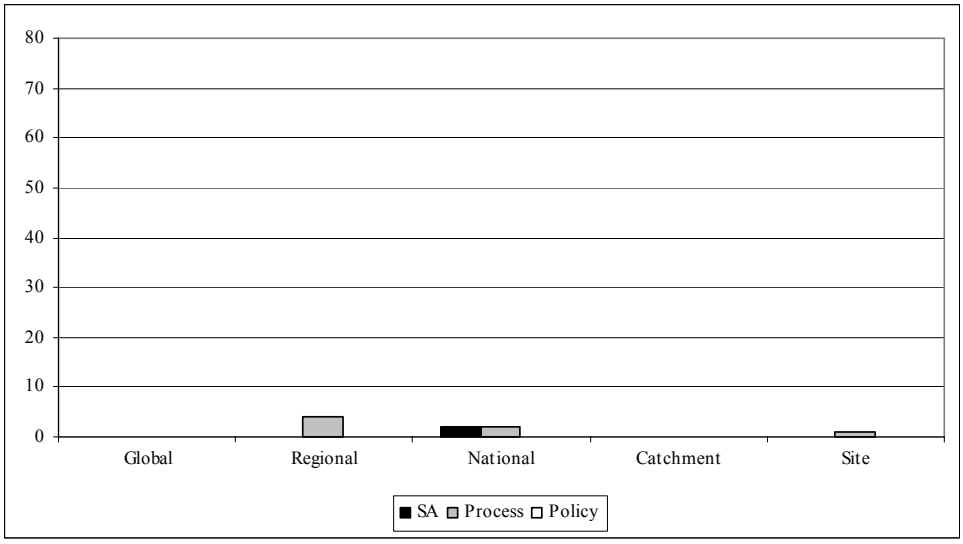

Figure 22: Number of WRC research records per scale and per level within the marine component of the hydrological cycle (n=9).

4.1.3 Terrestrial

The majority of research on the terrestrial component of the hydrological cycle has been undertaken within the Upper Orange and Middle Vaal WMAs (**Figure 23**). The primary focus of research has been on crop water requirements, the hydraulic properties of soils and on water treatment processes.

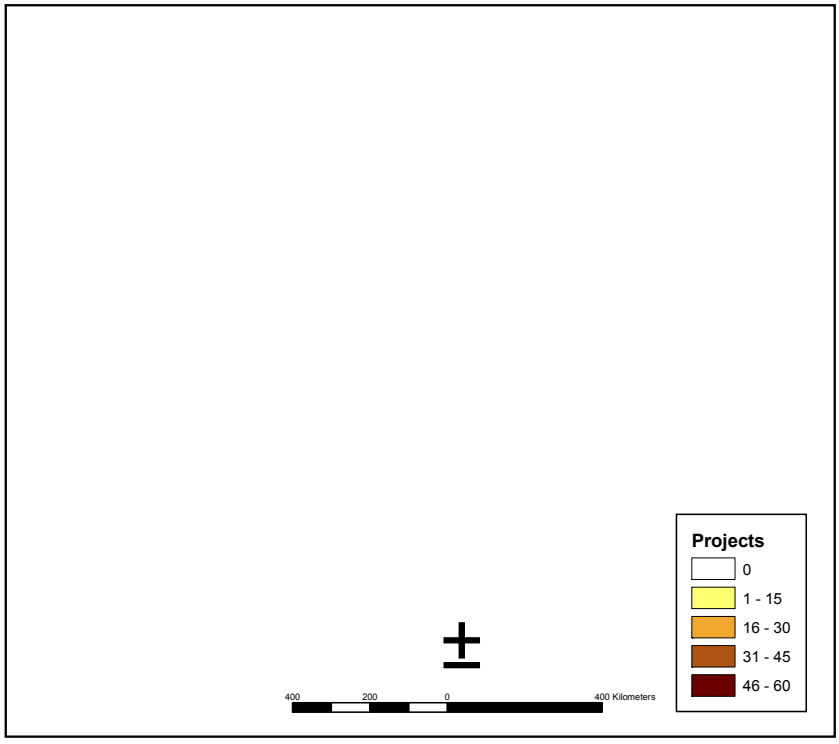

Figure 23: Number of WRC research records per tertiary catchment within the terrestrial component of the hydrological cycle (n=118).

Research at all scales of study has been conducted within this component of the hydrological cycle (**Figure 24**). However, the primary focus is at the national scale where process orientated research has been the main focus of attention.

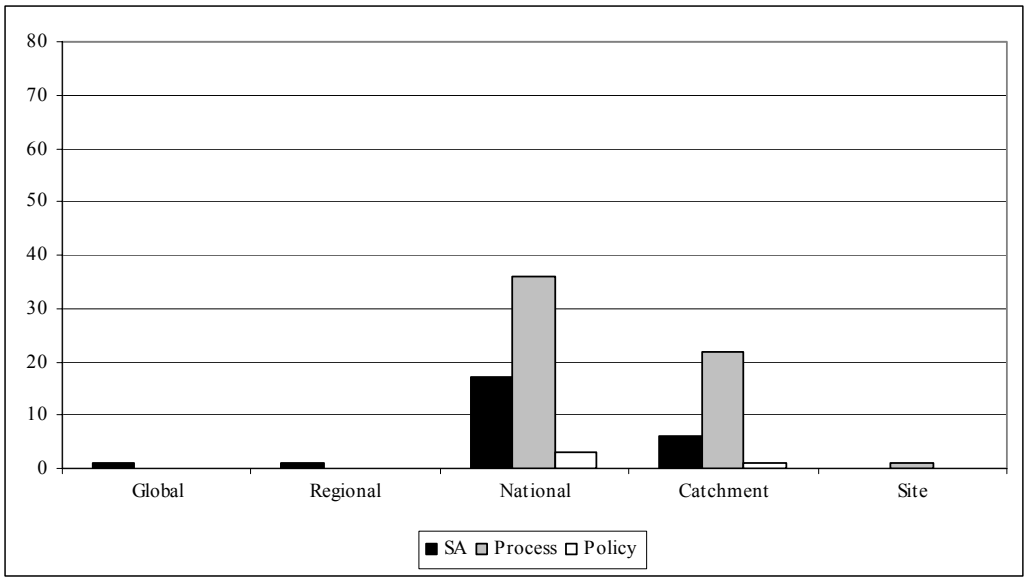

Figure 24: Number of WRC research records per scale and per level of study within the terrestrial component of the hydrological cycle (n=118).

4.1.4 Atmospheric

The majority of the research within the atmospheric component of the hydrological cycle has been conducted along the along the Orange and Vaal river systems where research on evaporation and water balance processes has been the primary focus (**Figure 25**).

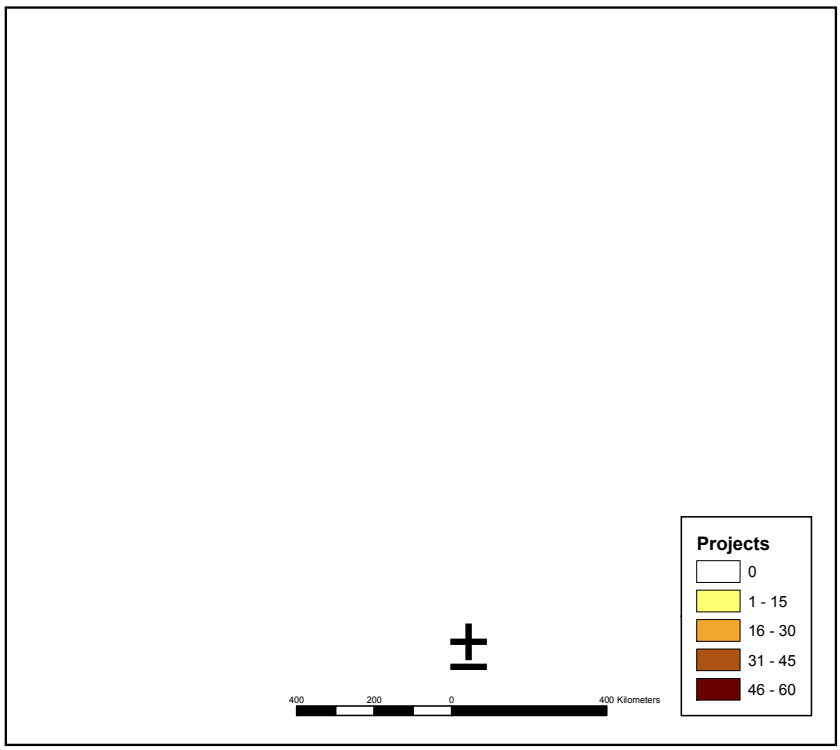

Figure 25: Number of WRC research records per tertiary catchment within the atmospheric component of the hydrological cycle (n=42).

The primary focus of research is at the process level, and has been conducted at both regional and national scales (**Figure 26**). No policy related research has been undertaken for the atmospheric component of the hydrological cycle.

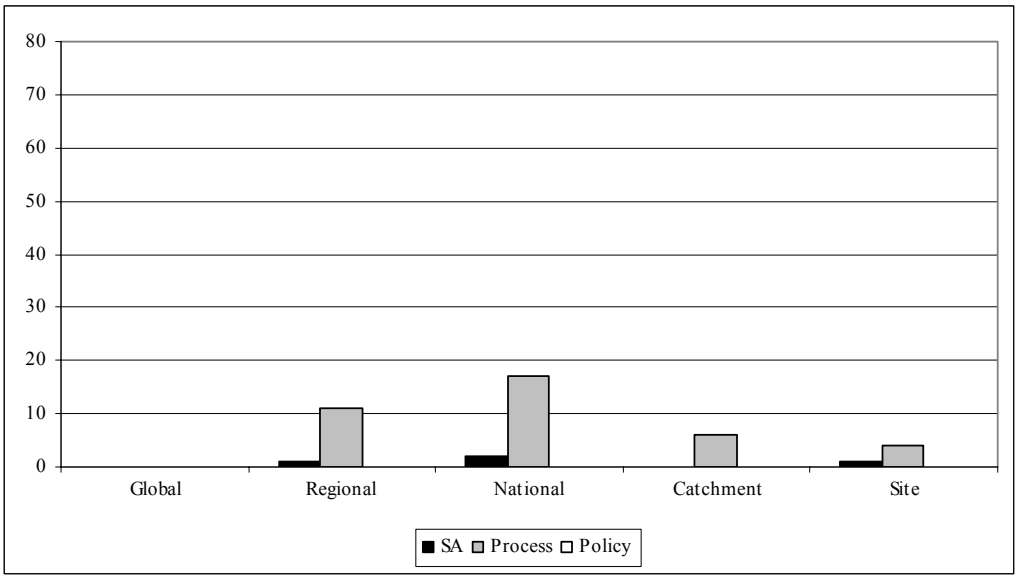

Figure 26: Number of WRC research records per scale and per level, within the atmospheric component of the hydrological cycle (n=42).

4.1.5 Subterranean

Although relatively few research projects have been conducted on subterranean component of the hydrological cycle, the research has had a relatively higher coverage in terms of the tertiary catchments within South Africa, generally because the scale of individual projects tends to be relatively broad (**Figure 27**). The primary focus of research has been on the development of groundwater as a water resource, (especially in terms of its suitability as a source of potable water for rural communities), and the vulnerability of groundwater to pollution and abstraction. Some attention has also been focused on the underground waters of coastal aquifers since these provide relatively important sources of water for many coastal communities and sensitive coastal ecosystems.

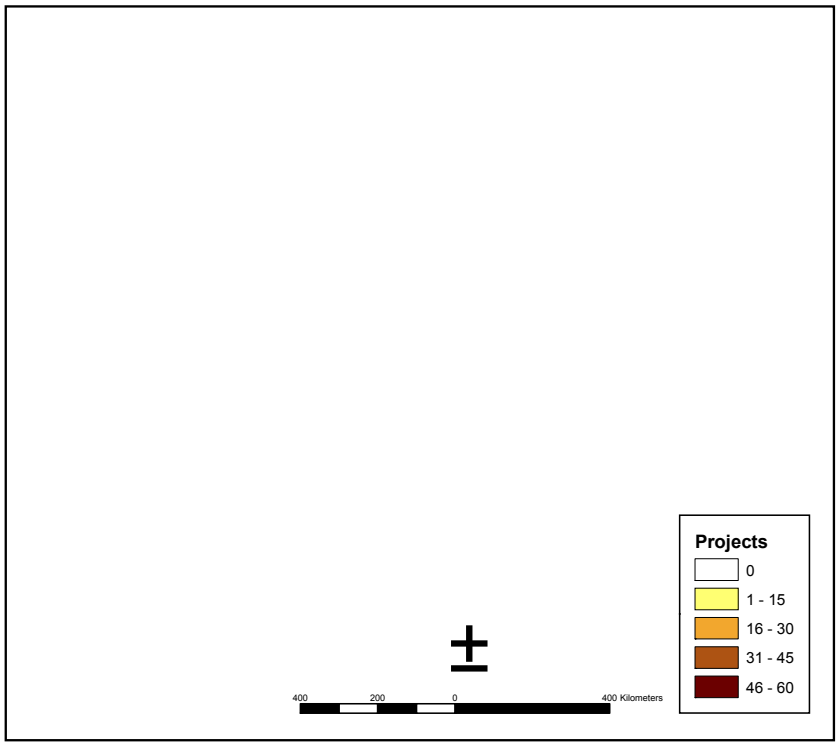

Figure 27: Number of WRC research records per tertiary catchment within the subterranean component of the hydrological cycle (n=105).

The majority of research has been site-specific and has been conducted at the process-orientated level (**Figure 28**). The few studies conducted at a national scale have been focused on situation assessments such as the development of groundwater atlases. In addition, several important studies have been conducted on ground water availability along the coastal zone of South Africa, with a particular emphasis on the availability and suitability of these water supplies for domestic use.

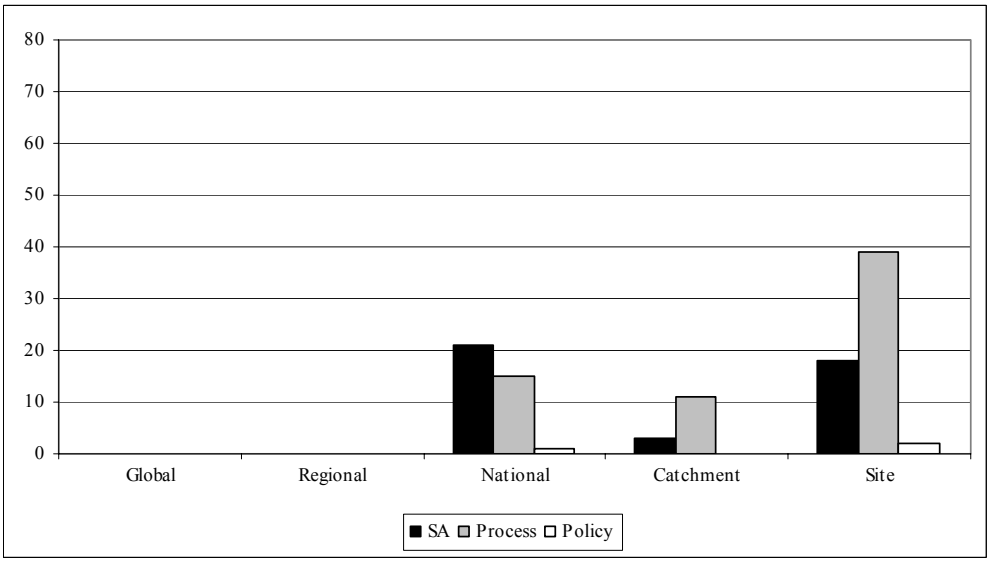

Figure 28: Number of WRC research records per scale and per level, within the subterranean component of the hydrological cycle (n=105).

4.2 Analysis of DWAF Records

4.2.1 Aquatic

The number of records within the aquatic component of the hydrological cycle in terms of the relationship between the level and scale of the research is illustrated in **Figure 29** below. The majority of the research has been undertaken at a catchment and national level where the focus has been on situation assessments. The type of research undertaken has centred on basin studies for the various primary drainage basins in South Africa comprising studies on water infrastructure, water demand and use, hydrology and reserve determinations.

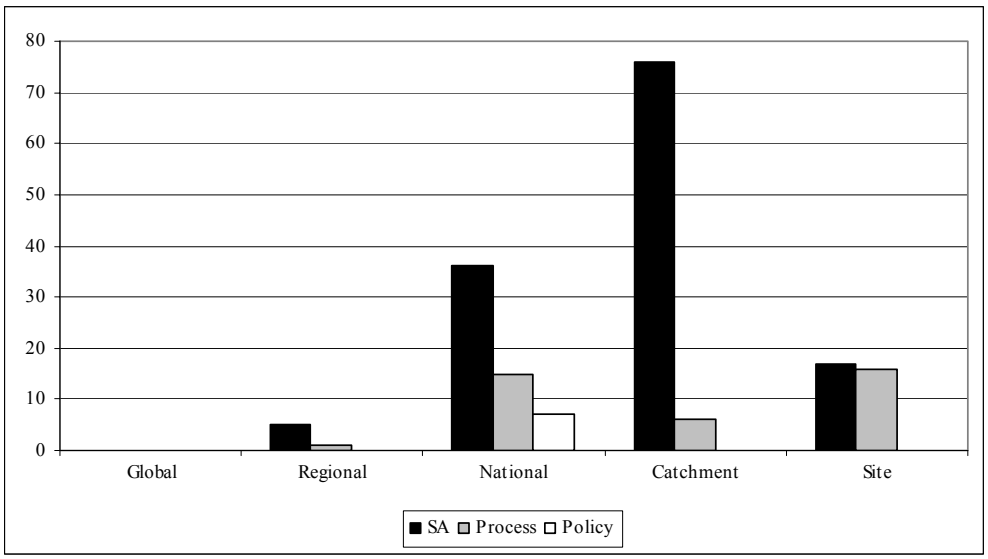

Figure 29: Number of DWAF research records per scale and per level within the aquatic component of the hydrological cycle (n=179).

4.2.2 Marine

There are no DWAF records for marine related research.

4.2.3 Terrestrial

Research at the national, catchment and site-specific scales have been primarily focussed on a process-based level (**Figure 30)**, where the specific areas of research were mostly related to water treatment, crop requirements and pollution controls. No policy research has been undertaken in the terrestrial component and no studies have been undertaken at global and regional scales.

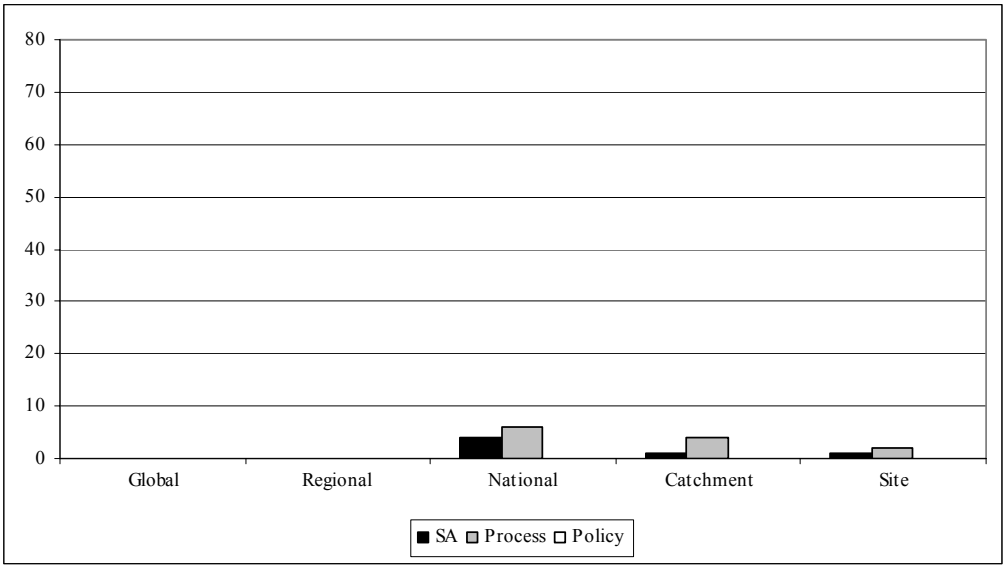

Figure 30 Number of DWAF research records per scale and per level within the terrestrial component of the hydrological cycle (n=18).

4.2.4 Atmospheric

Of the seven records that have been designated as atmospheric related research, five were undertaken at the situation assessment level at the regional and national scales (**Figure 31**). These investigations focused on precipitation studies and tropical cyclone investigations.

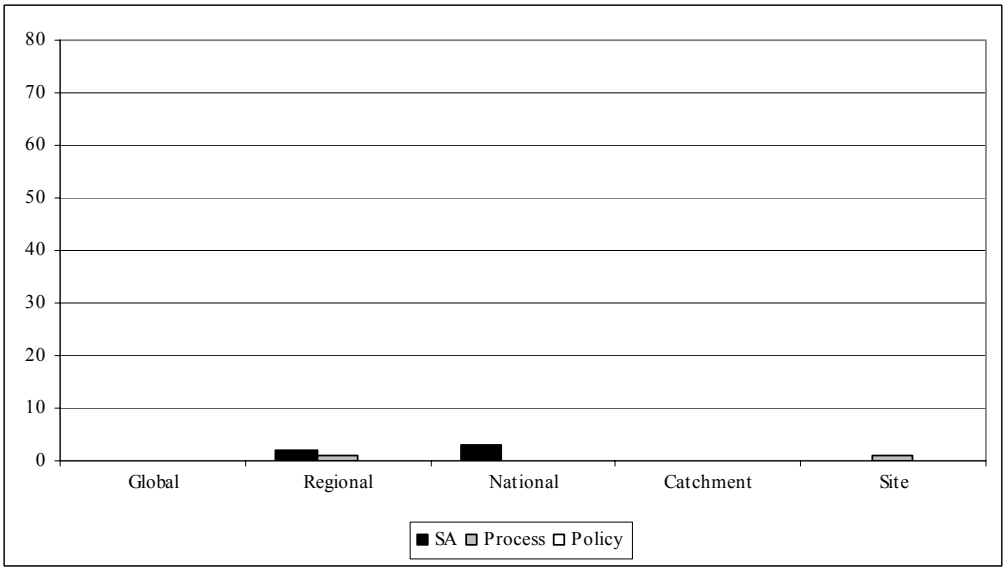

Figure 31 Number of DWAF research records per scale and per level within the atmospheric component of the hydrological cycle (n=7).

4.2.5 Subterranean

Research related to the subterranean component of the hydrological cycle has been undertaken at the national, catchment and site specific level and has focused primarily on situation assessments (**Figure 32)**. Research on groundwater supplies and geohydrology has been undertaken at a national scale and at the site-specific level.

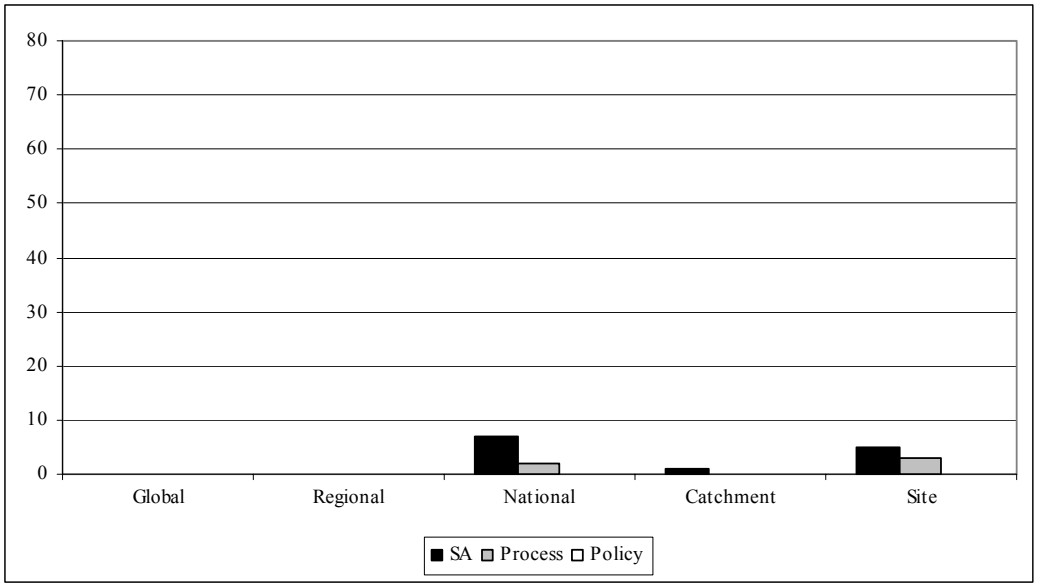

Figure 32: Number of DWAF research records per scale and per level within the subterranean component of the hydrological cycle (n=18).

4.3 Conclusion

In theory, there should be a natural progression in research effort, from initial situation assessment studies, through process-orientated research, to research that focuses on providing a foundation for policy development, or for the analysis of the implications of existing policy. This trend or transition of research is most clearly evident in the aquatic component where initial situation assessments led to the subsequent development of in-stream flow requirement methodologies and, subsequently, the derivation of in-stream flow requirements for specific catchments. However, this type of clear transition is seldom seen for other components of the hydrological cycle. Indeed, the situation is often aggravated or worsened by the long lag times between the completion of a research project or programme of research, and the uptake of these outputs into policy directives and instruments or management actions and decisions.

5. ANALYSIS OF ALL ISSUES

An initial list of priority research issues was developed from the thrust and programmes that were identified during the development of a strategy for the domain *Water and the Environment*, within the thrust *Environmental Functioning Within the Hydrological Cycle* (MacKay et al., 2004). This list of issues was finalized after consultation with a select group of experts and these issues are believed to represent the most important current, emerging or foreseeable concerns related to water in the environment in the next 3 to 8 years.

Each research record entered into the database was assigned to one or more of the issues that were regarded as relevant to the research undertaken. Each issue is phrased as a research question that needs to be answered in future discussion papers, projects and programmes. The records that are assigned to a particular issue are therefore intended to form part of the literature review / compilation of background information for these future studies. Importantly, this categorization of research records does not necessarily mean that a specific issue was addressed directly by the relevant research projects. Instead, the information that is contained within the research record should be seen as being relevant to the specific issues, and potentially providing useful background inputs that could be used to guide directed research that needs to be undertaken to resolve these issues. The different issues (1 to 27) are described briefly in **Table 14**.

The overview of the issues analysis is divided into 3 subsections: Section 5.1 refers to the analysis of the WRC records and Section 5.2 describes the analysis of the DWAF. A detailed analysis of the issues for the WRC records is presented in **Appendix A**.

Table 14: List of priority research issues.

Programme 1: Regional and global changes in the (biophysical) environment
1. What are the implications of climate change for the amount, timing, variability, flow-related quality and assurance of water supply?
2. What are the implications of climate change scenarios for background water quality in South Africa's biogeoclimatic regions, and their consequences for water treatment technologies and policies, and in-stream water quality management policies and regulatory mechanisms?
3. What are the potential impacts of global and regional climate change on nitrogen cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?
4. What are the potential impacts of global and regional climate change on phosphorus cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?
5. What are the implications of climate change for existing and new water sharing agreements?
6. What are the projected rates and patterns of desertification (caused by both climate change and land use practices), and their associated impacts on components of the hydrological cycle? What are the potential impacts of current and projected water use and management scenarios on desertification processes? What might be appropriate policy and regulatory responses?
7. What are the implications of meeting the Millennium Development Goals (MDGs) for water services & sanitation on environmental functioning within the hydrological cycle, and hence for water resources management?
8. What are the scope and significance of the impacts of current and projected patterns of atmospheric emissions (loads, concentrations, spatial distribution, forms {NOx, SOx, particulates, organics, carbon compounds}) from land-based activities for the hydrological

cycle and hence for water resources management? What are the environmental processes governing the fate and transport of these substances within the hydrological cycle? What are the options for policy responses from the water sector or in collaboration with other sectors?
9. What are the current and projected patterns of migration and urbanization? What are the potential impacts on water in the environment, either directly as a result of land use changes and/or discharges, or indirectly through changes in water demand patterns?
10. What are the scope and significance of past, current and projected patterns of use of persistent organic pollutants (POPs) in the environment? What are the environmental processes governing the fate and transport of POPs within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?
11. What is the current and projected status of both natural and human-induced radioactivity in the components of the hydrological cycle? What are the environmental processes governing the fate and transport of radioactivity within the hydrological cycle? What are the potential impacts on water resources, in terms of use and protection? What are the possible policy and regulatory responses?
12. What are the scope and significance of past, current and projected patterns of use of persistent toxic inorganic pollutants in the environment? What are the environmental processes governing the fate and transport of persistent inorganic pollutants (PIPs) within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?
Programme 2: Biodiversity
13. What secondary and/or tertiary effects is climate change (temperature, hydrology) likely to have on the structure, function and composition of ecosystems related to the components of the hydrological cycle? What are the implications for the quality, reliability and availability of water and associated goods and services derived from water resources? What are the options for policy responses?
14. What are the impacts of existing and proposed inter-basin transfer schemes on the structural, functional & compositional aspects of biodiversity at all scales (genetic to landscape)? What are the options for policy and regulatory responses?
15. What are the upstream impacts of flow-regulating structures, including dams, reservoirs and weirs? What are the potential ecological roles within the hydrological cycle of flow-regulating structures in surface water bodies? What are the implications for water resources management?
16. How does the current and emerging suite of WRM indicators reflect the dimensions (structure, composition and function) and scales (genetic to landscape) of biodiversity? What would be the characteristics of appropriate indicators for WRM that properly reflect all the dimensions and scales of biodiversity?
Programme 3: Impact and management of introduced species
17. What are the potential impacts on water resources of the widespread or commercial introduction of Genetically Modified Organisms (GMOs) into the environment, and what are the implications for policy and regulation of GMOs?
18. What is the extent and potential impact of nuisance species (terrestrial and aquatic; fauna and flora; alien and indigenous) on environmental functioning within the hydrological cycle?
Programme 4: Interfaces
19. What is the contribution of freshwater, derived from land, but not delivered through river mouths or estuaries, to the nearshore marine zone? What is the ecological significance of this contribution? What are the implications for water resources management?
20. What are the distribution and the current & projected utilisation of deep (>500m) groundwater bodies in South Africa? What are the potential impacts (geochemical, geohydrological, ecological) of deep (>500m) groundwater extraction on the components of the hydrological cycle, and on environmental functioning within the hydrological cycle?

What are the implications for policy and regulation?
21. To what extent do artificial recharge practices impact on biochemical, geochemical, hydrological and ecological processes within the hydrological cycle? What are the implications for policy and regulation?
22. What is the role of groundwater-dependent ecosystems (those contained within aquifers, as well as Karst and cave systems) in regulating ecological processes between components of the hydrological cycle?
Programme 5: Resource directed measure (RDM)
23. What are the implications of climate change for the philosophical basis of in-stream flow requirements (IFRs) of aquatic ecosystems and the Reserve, the methodologies currently used to determine IFRs, and the status of existing environmental flow allocations? What are the options for policy responses?
24. What are the strategic research issues and key knowledge gaps related to the derivation of in-stream water quality criteria for aquatic ecosystems (freshwater and estuarine)? How should these be addressed?
25. Current methods for determination of IFR take little or no account of important ecosystem processes related to the integrity, functioning and resilience of those systems (e.g. oxygenation, metal sequestration, nutrient cycling, sediment-water interactions and sediment quality). How should/could existing and emerging methodologies be adapted to integrate these aspects into IFR determinations?
WRC Strategic Issues
26. What are the potential impacts of national, regional and NEPAD poverty alleviation policies and strategies on the hydrological cycle, and hence on the availability, quality and reliability of water resources?
27. What are the implications of HIV/AIDS scenarios for water use and water resources management (quantity and quality)?

5.1 Analysis of WRC Records

The number of research records that are potentially applicable to each issue is illustrated in **Figure 33**. It is important to note that the presence of a large number of research records against a particular issue, (for example: Issue 7), does not mean that all of this information has unequivocal and direct bearing on that issue. Similarly, the absence of research project records against a particular issue (e.g. Issues 17, 19, or 27) does not mean that none of the information available has any bearing on that issue. Instead, it is clear that much of the available information is likely to have an indirect bearing on several issues and is beyond the scope of analysis conducted within this report. Additionally, there is also clear evidence that research directed at some issues - such as Issue 27, relating to HIV/Aids implications for the water sector – is not yet funded by any water research organization in South Africa, despite its rapidly rising importance. Whilst it is likely that this state of affairs will change soon, almost all of the current research in this arena is funded by international donor organizations (e.g. the European Union funded research directed by the SADC Health Sector Coordinating Unit) or by medical research institutions.

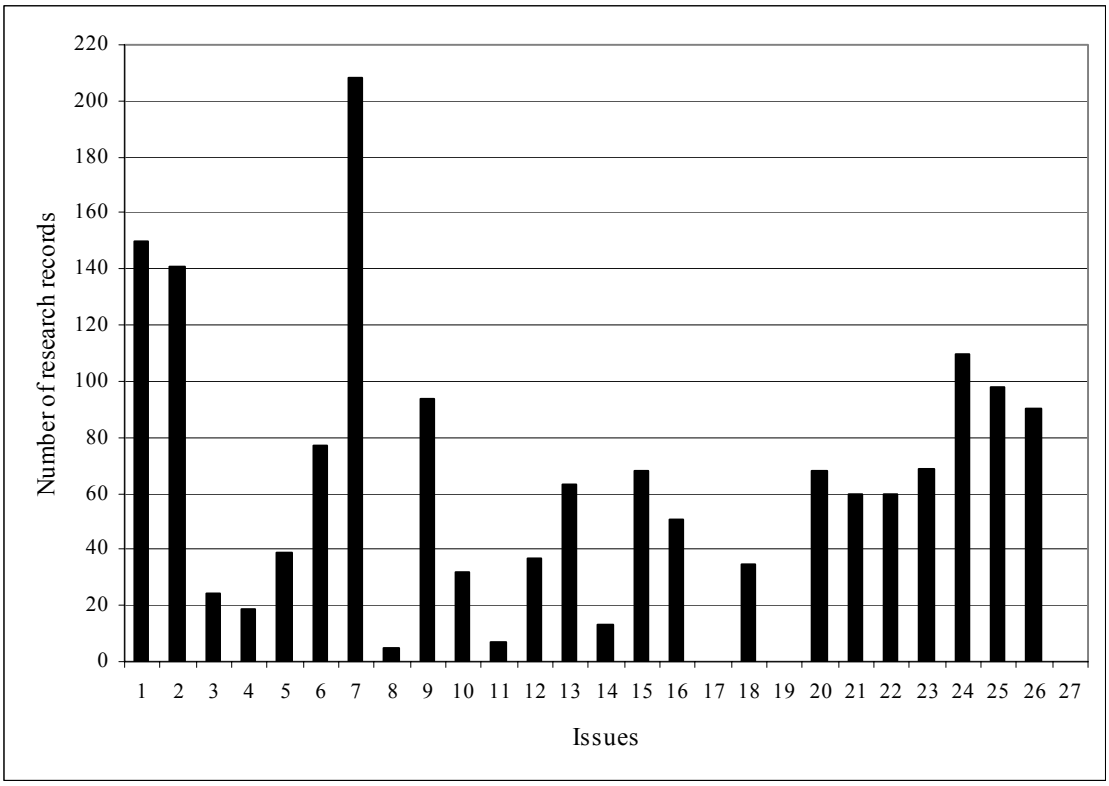

Figure 33: Number of WRC research records per priority issue (n=1618).

When one examines the number of research records per level of study for each issue, it is evident that for all issues, except Issue 5: Climate change and water sharing agreements (where situation assessments are in the majority), most of the relevant research has been process orientated (**Figure 34**).

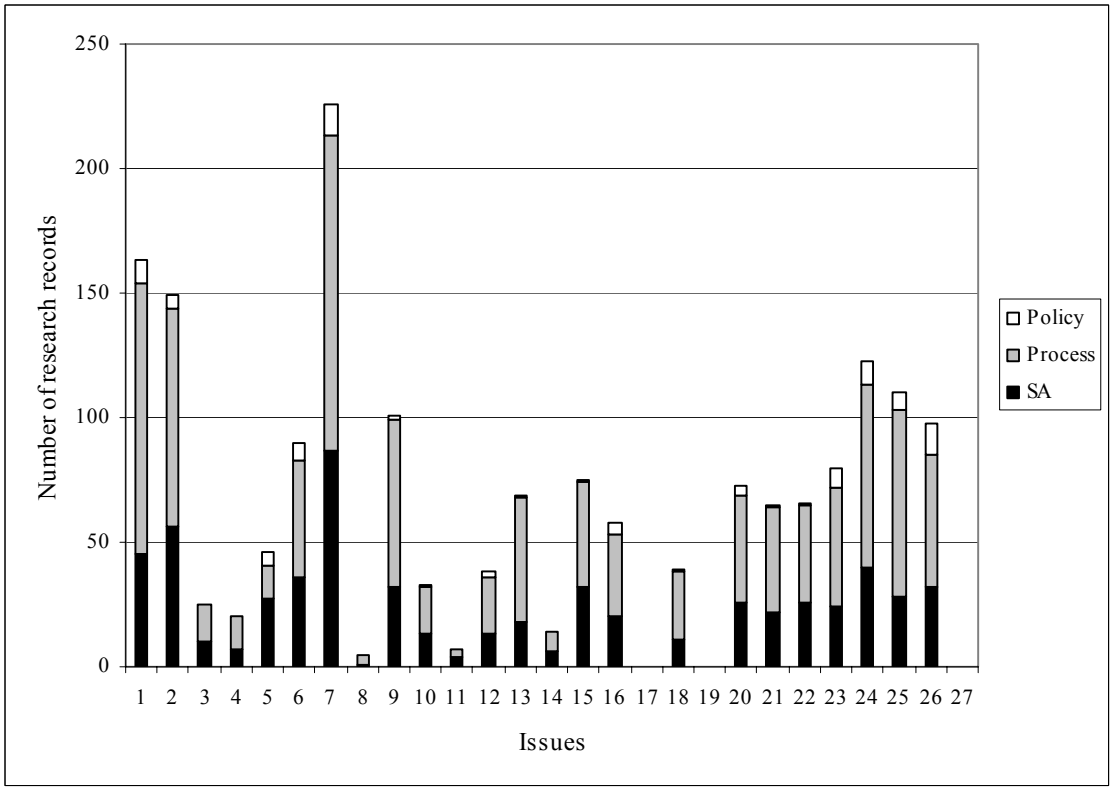

Figure 34: Number of WRC research records per issue, per level of study (n=1618).

For most issues, the majority of relevant research has been conducted at national scale, with a few exceptions where catchment scale studies are more numerous (**Figure 35**). These exceptions include Issue 1: Climate change and water resources availability; Issue 5: Climate change and water sharing agreements; Issue 6: Desertification; Issue 8: Atmospheric emissions and impact on water resources; and Issue 15: Upstream impacts and the ecological roles of flow regulating structures.

Those issues where some relevant research was undertaken at a global scale include Issue 2: Climate change and background water quality; Issue 12: Persistent inorganic pollutants; Issue 14: Biodiversity and IBTs; and Issue 15: Upstream impacts and ecological roles of flow regulating structures. At a regional scale, most of the relevant research was conducted for Issue 1: Climate change and water resources availability, with a total of 17 records. On a site-specific scale, the highest number of research records, 59, is for Issue 7: Implications of MDGs for water resources.

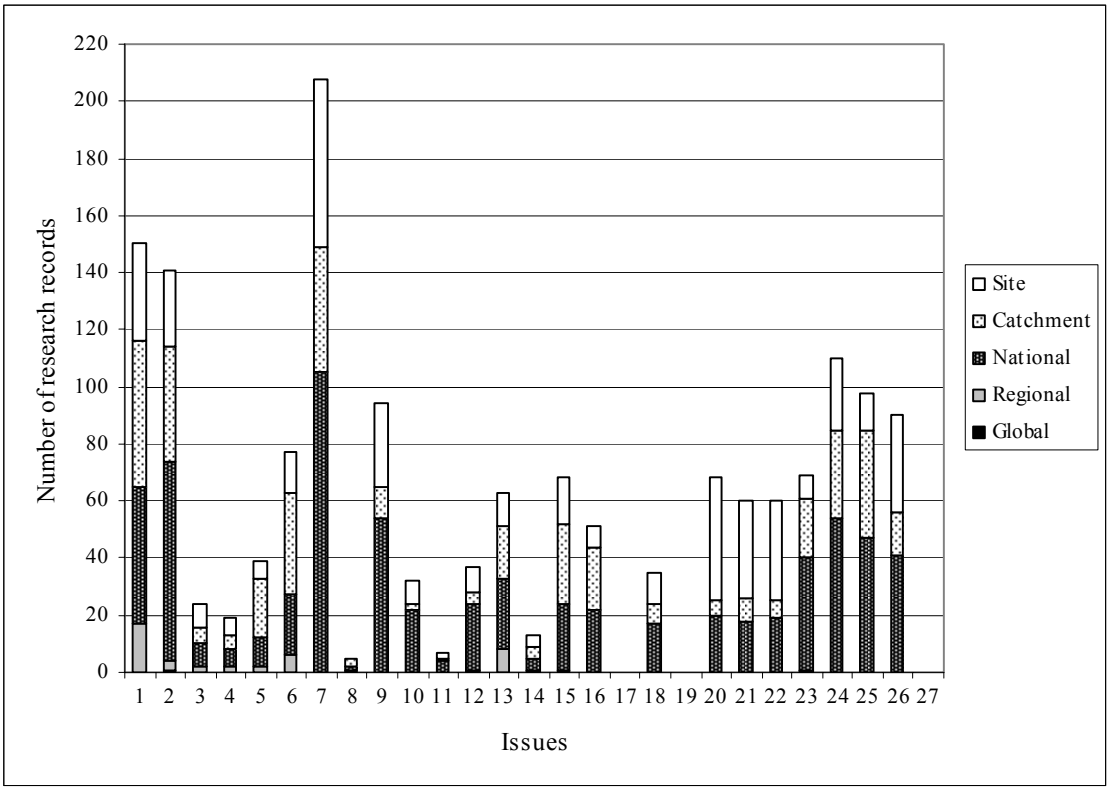

Figure 35: Number of WRC research records per issue, per scale of study (n=1618).

5.2 Analysis of DWAF Records

The number of research records that are potentially relevant to each of the priority issues is illustrated in **Figure 36**. Issue 1: Climate change and water resources availability has the most records that are relevant to it (146 records). It must however be pointed out that this is a very broad issue and most of the pertinent research is in the area of water resources availability and is not linked directly to climate change. But these records could provide useful background information to develop a directed research programme. Issue 16: Biodiversity in WRM indicators has 55 records associated with it – these were primarily basin studies that would provide largely background information for more focused research about the issue. Although Issue 5: Climate change and water sharing agreements; Issue 17: Implications of GMOs; and Issue 19: Freshwater requirements of the nearshore marine zone have no records associated with them, this does not imply that no relevant research has been undertaken, but simply that DWAF has not prioritised or commissioned research in this field.

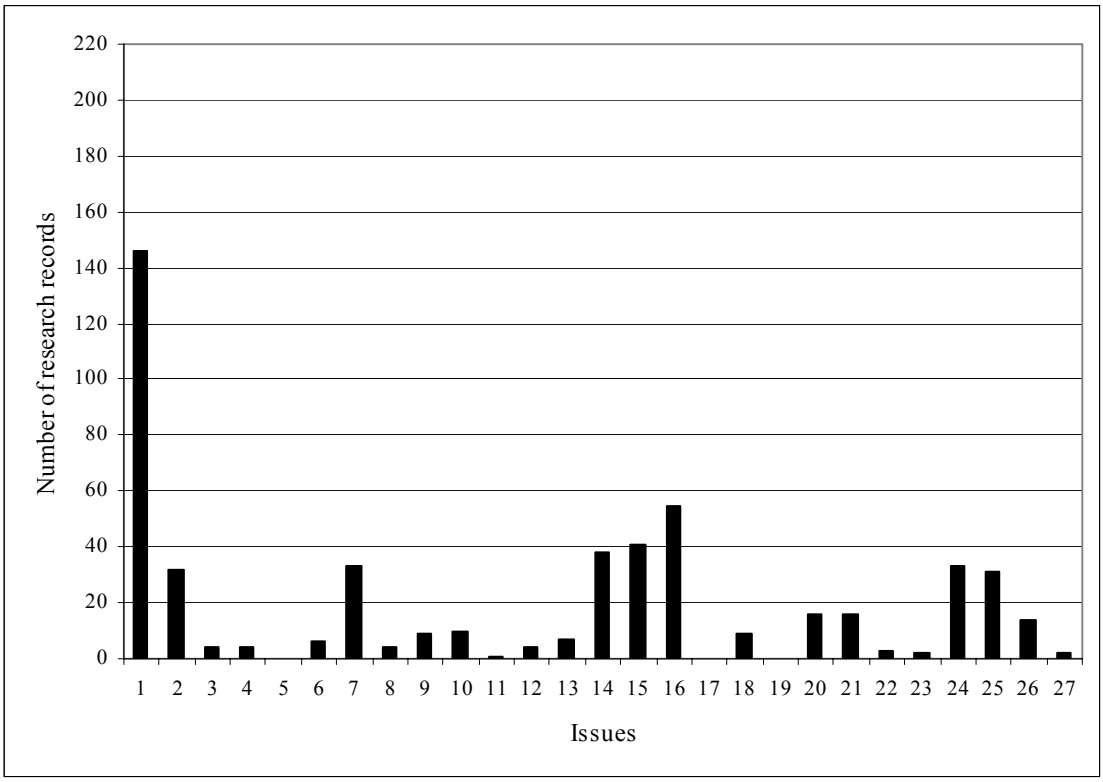

Figure 36: Number of DWAF research records per priority issue (n=520).

When the number of records per issue is examined in terms of the level of study, it is evident that for the four issues with the majority of records associated with, Issues 1, 14, 15 and 16 are primarily situation assessments (**Figure 37**).

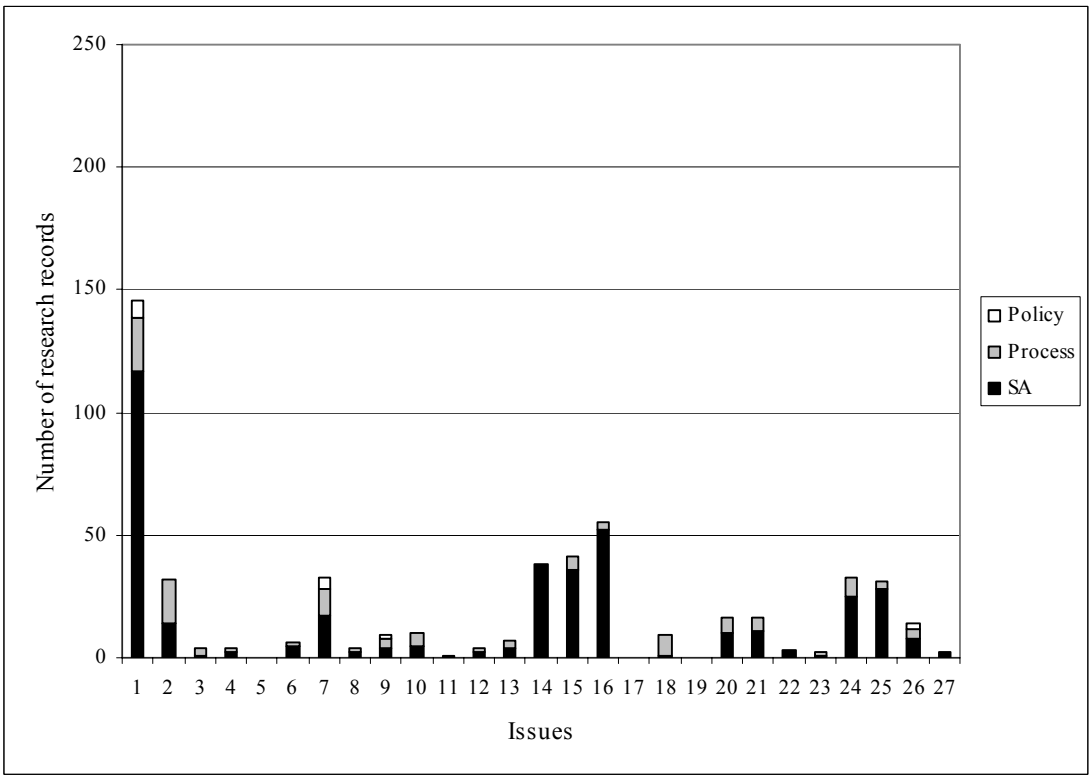

Figure 37: Number of DWAF research records per issue, per level of study (n=520).

For the majority of issues, relevant research has been undertaken at a catchment scale. However for some issues, for example Issue 7: Implications of MDGs for water resources and Issue 26: Impacts of national regional and NEPAD poverty alleviation policies and strategies, most of the research was conducted at a national scale (**Figure 38**).

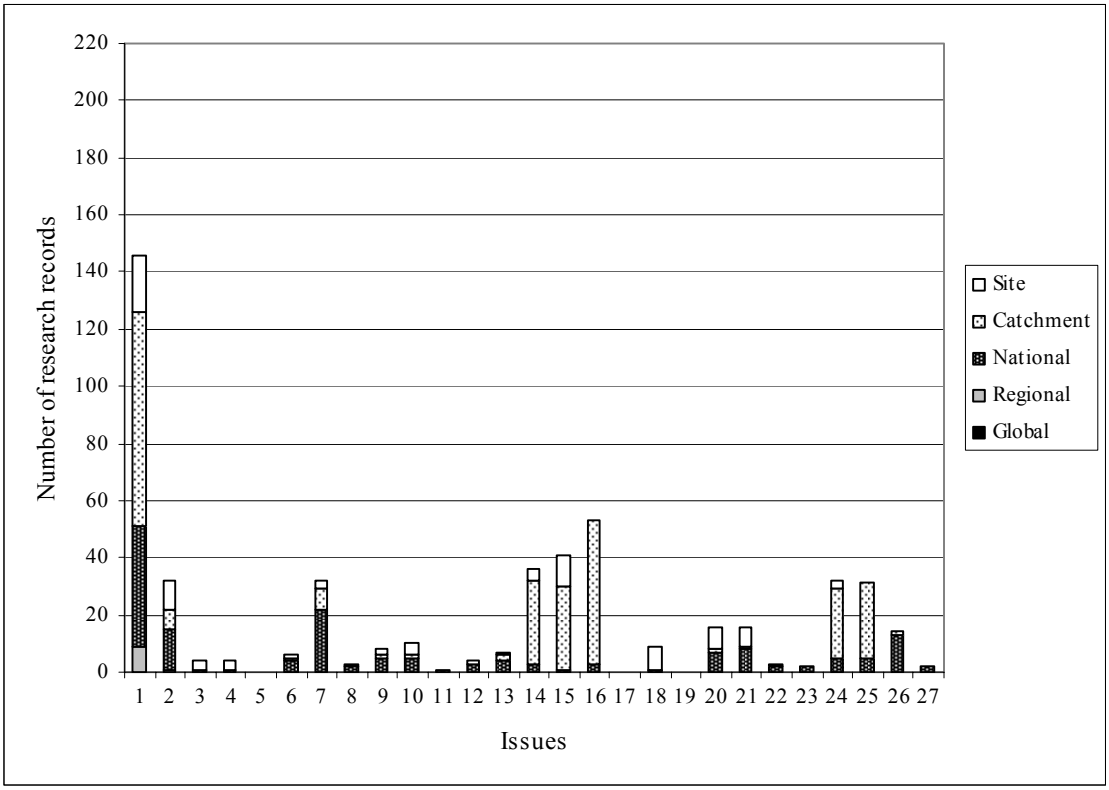

Figure 38: Number of DWAF research records per issue, per scale of study (n=520).

6. SUMMARY OF ISSUES

Table 15 is a summary of the discussion of the status of each research issue and the implications for the Water Research Commission in terms of providing guidance, support or leadership.

Table 15: Discussion of the status of each research issue.

Programme 1: Regional and global changes in the (biophysical) environment
1. What are the implications of climate change for the amount, timing, variability, flow-related quality and assurance of water supply?
To date, the Water Research Commission has funded very little policy-level research related to climate change issues. Whilst it is clear that this issue has the potential for enormous ramifications at national, regional, continental and global scales, it is not strictly a water sector responsibility to drive national policy development in this field. It would be more appropriate for this issue to be led by the Department of Environment Affairs and Tourism (DEAT), since this department has the national mandate to drive national policy development related to climate change issues. Nevertheless, the insights, experience and knowledge contained within the water sector could provide important inputs to both national and regional policy formulation and should not be ignored. An important insight is that much of the international experience related to climate change issues has recognized that the potential consequences of global climate change have implications for both the blue and green water components of the hydrological cycle. Given the range, scale, variability and potential implications of global climate change for southern Africa, South African research expertise has considerable potential to derive new insights into the green water components of the hydrological cycle in particular. In addition, there is a clear need for a comprehensive cross-sectoral policy response to climate change issues since there is incomplete evidence that climate change will indeed affect all aspects of the hydrological cycle. Here, it will be necessary to ensure that these efforts consider all the aspects of landuse that could potentially affect components of the hydrological cycle.
2. What are the implications of climate change scenarios for background water quality in South Africa's biogeoclimatic regions, and their consequences for water treatment technologies and policies, and in-stream water quality management policies and regulatory mechanisms?
At first sight, much of the information that is available would appear to be indirectly related to this issue of concern. However, because much of the research has been process-orientated, the findings often have a far wider application that the original study site where the research was undertaken. Once again, national policy-level research should fall within the mandate of the Department of Environment Affairs and Tourism, with water sector contributions providing enhanced insights that could shape specific decisions. Nevertheless, the Water Research Commission can play a leading role within the water sector by assisting with the development of water-related policy that deals with the water quality implications of potential climate change scenarios.

3. What are the potential impacts of global and regional climate change on nitrogen cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?

Much of the original research emphasis that was placed on nitrogen cycling processes was linked to, or associated with, the investigations into eutrophication processes that dominated aquatic research in the 1970s and early 1980s. Important eutrophication research findings demonstrated that most natural (unmodified) African waters are deficient in both nitrogen and phosphorus, though natural processes of biological nitrogen fixation could soon replenish inorganic nitrogen stocks required by aquatic organisms. Therefore, interventions designed to reduce the availability of nitrogen for aquatic organisms seldom offered practical solutions to eutrophication problems. Instead, phosphorus was identified as the critically limiting nutrient for the (nuisance) growth of algae and aquatic plants and the focus of most eutrophication research turned towards the development of strategies to reduce phosphorus inputs to aquatic ecosystems, and culminated in the promulgation of the 1 mg/litre concentration limit for total phosphorus in the Special Effluent Standard. Whilst this approach offered some relief from pervasively high levels of eutrophication, the "allowable" phosphorus limit of 1 mg/litre in effluents has had limited success in curbing eutrophication. Man-made reservoirs that receive treated effluent in their inflows have also been shown to be the sites for significant "sinks" for nitrogen. In some heavily enriched reservoirs, up to 50% of the inflowing total inorganic nitrogen load may be lost to the atmosphere through denitrification processes.

Much of the process-level information on nitrogen cycling has potentially useful applications in studies on the possible implications of climate change. In particular, the results of field and laboratory studies that related nitrogen cycling processes to prevailing water temperature dynamics can provide fundamental insights into the potential implications of climate change.

An additional important insight arising from research projects conducted on different aspects of the nitrogen cycle is that, despite being nitrogen deficient in relative terms, the cumulative total loads of nitrogen in river systems appears to have increased over time and this has resulted in increased nitrogen loadings to the near-shore marine zone. If correct, this has great significance for the ecological functioning of sensitive estuarine and coastal systems.

4. What are the potential impacts of global and regional climate change on phosphorus cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?

Interestingly, much of the research capacity that was originally developed during research projects aimed at understanding the phosphorus cycle in freshwater ecosystems (eutrophication studies in rivers and reservoirs), was later focussed on studies of the potential of wetland ecosystems as passive and active phosphorus

removal systems to remove phosphorus from effluents. Much of this research emphasis was subsequently transferred to studies of the in-stream flow requirements of a variety of aquatic organisms that occupy different aquatic habitats (e.g. rivers, lakes, pans, reservoirs, wetlands), as well as large-scale catchment studies. In most of these cases, relatively limited attention was paid to issues of phosphorus cycling, because of the continued failure to convince water resource managers that the Special Phosphorus Standard of 1 mg/litre was too high, and should be lowered to approximately 0.1 mg/litre as a matter of urgency. Consequently, eutrophication issues that centre on phosphorus cycling processes remain a key concern to this day.

The few field and laboratory studies on phosphorus cycling processes in aquatic ecosystems have direct relevance for evaluations of potential implications of climate change on phosphorus cycling in all components of the hydrological cycle. The bulk of the recent research has been aimed at phosphorus removal or inactivation processes in conventional and novel water treatment systems, rather than on the fate and transport of phosphorus in aquatic ecosystems.

5. What are the implications of climate change for existing and new water sharing agreements?

No research projects have been directed precisely at this research question, though several research programmes have provided useful insights that could form the basis for future research. In view of the increasing sensitivity around issues of trans-national and inter-sectoral sharing of scarce water resources, and the equitable allocation of water between countries that share a common river basin, this issue is rapidly gaining international prominence and needs to be resolved. The South African Government and its Department of Water Affairs and Forestry has entered into a large number of bi-lateral and multi-lateral agreements with neighbouring countries – these are aimed at improving the collective water resource management efforts of the countries concerned in their shared river basins. Future collaborative, basin-scale studies will be needed to determine the likely extent and implications of possible climate change effects and how these shared water resources can best be managed over the long-term by the respective countries.

6. What are the projected rates and patterns of desertification (caused by both climate change and land use practices), and their associated impacts on components of the hydrological cycle? What are the potential impacts of current and projected water use and management scenarios on desertification processes? What might be appropriate policy and regulatory responses?

South Africa has ratified the United Nations Convention to Combat Desertification and this places a certain level of obligation on the country to contribute to continental and global efforts in this arena. Here, again, the Department of Environmental Affairs and Tourism is the department charged with primary responsibility for South Africa's implementation efforts in this arena and should co-ordinate and lead the development of national policy in this field. Once again, the Water Research Commission can play a leadership role within the water sector

and support research that will assist the national policy development processes. The insights and experiences gained within the water sector represent an important contribution to our collective knowledge of the processes involved. Ultimately, a multi-sectoral policy response will be needed to resolve this issue and it will be essential for all sectors to converge and co-ordinate their efforts. The process level research that has been conducted to date could provide useful information for global- and continental-scale modelling studies. In addition, management of those river basins located in the drier portions of South Africa will benefit from the insights gained in these studies. Here, the Department of Water Affairs and Forestry, as well as the new Catchment Management Agencies, will need to play a central leadership role.

7. What are the implications of meeting the Millennium Development Goals (MDGs) for water services & sanitation on environmental functioning within the hydrological cycle, and hence for water resources management?

In broad terms, practically every research project funded by the Water Research Commission and the Department of Water Affairs and Forestry could contribute to this issue in several ways. An important, central issue: how to determine and then maintain a balance between resource utilization (to provide goods and services to society) and resource protection (to ensure that the water resources remain capable of providing these goods and services), forms the backbone of all water resource management goals. The Department of Water Affairs and Forestry will require each of the new Catchment Management Agencies to draw up and implement appropriate plans to provide water supply and sanitation services in their areas of responsibility.

8. What are the scope and significance of the impacts of current and projected patterns of atmospheric emissions (loads, concentrations, spatial distribution, forms {NOx, SOx, particulates, organics, carbon compounds}) from land-based activities for the hydrological cycle and hence for water resources management? What are the environmental processes governing the fate and transport of these substances within the hydrological cycle? What are the options for policy responses from the water sector or in collaboration with other sectors?

There has been (and will be until resolved) considerable dissent amongst researchers, industrialists and water resource managers around the scale, extent and severity of possible consequences of atmospheric emissions on South Africa's water resources. Typically, these differences of opinion centre on the "size" and "characteristics" of the emissions, where (and how) these could potentially influence terrestrial and aquatic ecosystems, and their likely consequences for human populations. The result has been that there is no significant advance in national policy responses to manage and mitigate the potential consequences.

This polarized debate is not new and cannot be resolved in a simplistic way by merely repeating studies that have been carried out in the past in an effort to "improve the numbers". Instead, there is an acute need to design an appropriate collaborative study that engages all stakeholders, and which extends over an appropriate scale, which will provide unequivocal evidence as to the quantitative

extent and forms of atmospheric emissions, their spatial distribution across the southern African landscape, the forms in which materials are deposited on specific landscape units, and their subsequent fate. Closely-related issues such as the impacts of specific atmospheric emission components and compounds on soil structure and chemistry, vegetation physiology, crop productivity, and food and water security need to be addressed with a multidisciplinary and multi-organizational approach. Both the Water Research Commission and the Department of Water Affairs and Forestry could play leading roles in convening and guiding this research effort, and ensuring that all uncertainties are properly addressed. This will allow a coherent set of national responses (spanning policy and operational activities) to be drawn up and implemented.

9. What are the current and projected patterns of migration and urbanization? What are the potential impacts on water in the environment, either directly as a result of land use changes and/or discharges, or indirectly through changes in water demand patterns?

The prevailing and projected patterns of population migration and urbanization are not fully understood and this hampers proper planning for the provision of a variety of services to formal and informal communities. These services include the provision of land, housing, potable water, sanitation, waste disposal and electricity supplies. The interacting influences of social, demographic, cultural, and economic drivers, together with the political imperatives to redress past inequities, have direct and indirect effects on the poverty levels of individuals and communities, and also influence personal preferences or options for specific geographic regions, or types and levels of economic activity. Clearly, the scope of this issue is far wider than the water sector alone, though the water sector has a pivotal role to play in assisting national efforts; in particular, the water sector can provide good guidance at policy level to prevent injudicious decisions that could adversely affect the country's water resources.

The Water Research Commission and other research funding agencies have supported several research projects that have focussed on understanding the causes and nature of runoff patterns from urban settlements, and the development of appropriate water treatment technologies to minimize the adverse impacts of poor quality runoff on aquatic ecosystems. Whilst this information is extremely important for proper management of urban settlements, our ability to predict the spatial and temporal patterns of migration and urbanization is still poor.

10. What are the scope and significance of past, current and projected patterns of use of persistent organic pollutants (POPs) in the environment? What are the environmental processes governing the fate and transport of POPs within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?

To date, relatively few research projects have been carried out on persistent organic pollutants though the topic is gaining prominence due to the United Nations Treaty on the control of these substances. A particular problem area has been the high cost of conducting chemical analyses for organic compounds, which

has hindered the implementation of routine monitoring programmes for these substances. This difficulty is compounded by the need to develop new analytical techniques to detect progressively greater numbers of new organic compounds that appear each year. These compounds include a wide variety of substances derived from the country's expanding chemical industry, as well as increased numbers of novel pharmaceutical products, including endocrine disrupting substances.

There is a pressing need for a national-scale survey and inventory of the current situation regarding the variety of organic compounds present in the different components of the hydrological cycle, so that attention can be directed to those areas where the greatest problems occur. In support of this effort, greater attention also needs to be paid to the fate and transport of these substances in the freshwater components of the aquatic environment, and their implications for ecosystem and human health.

11. What is the current and projected status of both natural and human-induced radioactivity in the components of the hydrological cycle? What are the environmental processes governing the fate and transport of radioactivity within the hydrological cycle? What are the potential impacts on water resources, in terms of use and protection? What are the possible policy and regulatory responses?

There is a need to conduct a broad-scale situation assessment of the extent and types of radioactivity present in the different components of the hydrological cycle in South Africa, and to determine the extent to which any radioactivity may be due to natural geological sources, or due to human activities, particularly the disposal of mining wastes. This will provide clear directions for the development of national policy by the Department of Water Affairs and Forestry, and will also allow the necessity for appropriate remedial measures to be evaluated and implemented on a site-specific or catchment-specific basis by the new Catchment Management Agencies.

12. What are the scope and significance of past, current and projected patterns of use of persistent toxic inorganic pollutants in the environment? What are the environmental processes governing the fate and transport of persistent inorganic pollutants (PIPs) within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?

Persistent inorganic pollutants consist principally of metal and semi-metal ions that exert a variety of toxic effects on aquatic and terrestrial organisms. These substances exist in many different forms and are derived from both natural geological causes and man-made activities. Several research funding organizations, including the Water Research Commission, have supported a number of research projects on these substances. Most projects have focussed on efforts to determine the extent and biological availability of these substances in freshwater aquatic ecosystems and estuaries, and evaluate their effects on specific groups of aquatic organisms. Whilst these studies have revealed the widespread presence of these toxic inorganic substances in many aquatic ecosystems, there is less understanding of the precise role and significance of

these substances in such ecosystems. Similarly, several studies have provided clear evidence that the majority of these substances have been derived from human activities, especially the disposal of mining and industrial wastes, and this information, together with specific toxicological studies, has formed the basis for the derivation of water quality guidelines for specific toxic inorganic substances. A smaller quota of research work has focussed on the fate and transport of these substances in aquatic ecosystems. As a result, our knowledge of the extent to which these substances may be bound within sediments and re-mobilized under specific sets of circumstances, as well as their precise implications for ecosystem structure and functioning, is incomplete and insufficient to formulate clear rehabilitation policies and methodologies.

The Water Research Commission is ideally placed to play a leading role in resolving these problems through the development of a national strategy to determine the extent, significance and potential for rehabilitation of the different toxic inorganic substances that are present in aquatic ecosystems. Ideally, targeted research should include clear assessments of the ways in which aquatic ecosystems act as temporary and permanent sinks for these substances. Since South Africa shares many of its river systems with neighbouring countries, these substances also pose potential problems for our neighbours. This situation needs to be clarified, and then supported by the development and implementation of appropriate policy instruments and management strategies. Here, the Department of Water Affairs and Forestry will need to play a leading role in specifying the types of research that are needed and how these research results will be incorporated into appropriate regulatory instruments.

Programme 2: Biodiversity

13. What secondary and/or tertiary effects is climate change (temperature, hydrology) likely to have on the structure, function and composition of ecosystems related to the components of the hydrological cycle? What are the implications for the quality, reliability and availability of water and associated goods and services derived from water resources? What are the options for policy responses?

None of the research projects funded by the Water Research Commission have focussed directly on the questions related to this issue. However, the information derived from several research projects has provided indirect information that has helped to extend and consolidate our knowledge and understanding of the potential indirect effects of climate change on several hydrological processes. This research arena has been identified as a high priority by the Water Research Commission and new research projects directed at deriving answers to some of the specific questions posed above will be based on the consolidated knowledge and understanding derived from earlier projects. Particular emphasis will be placed on gaining new knowledge of indirect and cumulative effects that are transmitted and transformed along the longitudinal axes of aquatic ecosystems.

14. What are the impacts of existing and proposed inter-basin transfer schemes on the structural, functional & compositional aspects of biodiversity at all scales (genetic to landscape)? What are the options for policy and regulatory responses?

A large proportion of the research that is relevant to this issue consists of review studies, where the information obtained for South African systems has been compared to similar studies conducted in Australia and North America. A major emphasis within South African research projects has been driven by concerns about the potentially dramatic alterations in riverine populations of aquatic organisms and the resulting adverse impacts on ecosystem functioning that are associated with both the donor and recipient systems linked by inter-basin water transfers. Whilst this work has provided useful insights into both general and specific ecosystem processes, there are still large gaps in our understanding of the effects of inter-basin water transfers on the structural, compositional and functional aspects of biodiversity. Similarly, our understanding of the comparative advantages and disadvantages linked to different structural configurations of inter-basin water transfer schemes is inadequate, though there is some understanding of specific engineering processes that could be deployed to minimize the transfer of biological material between donor and recipient systems.

Given the progressively increasing demands for water, several South African river basins are approaching closure where there is little available water that can be allocated to meet demands for water. A similar situation exists in several of our neighbouring countries. This will inevitably lead to an increase in the transfer of water from "water-rich" catchments to "water-poor" catchments, thereby increasing the likelihood that significant biological changes could occur at scales from genetic modification to population transformation. Additional concerns are linked to the inter-basin transfer of alien fish and crustacean species that were originally introduced for angling or aquaculture purposes. The situation could be compounded in future if the postulated long-distance transfers of water from rivers as far north as the Zambezi and Zaire systems are realized. At present, our knowledge levels are insufficient to allow the provision of unequivocal inputs to the formulation of appropriate policy responses. Therefore, a comprehensive situation analysis is required of the state of inter-basin water transfers throughout the entire southern African region, as well as focussed research projects to determine the specific effects of inter-basin water transfers on biodiversity. This will then form a firm foundation for the development of appropriate policy.

15. What are the upstream impacts of flow-regulating structures, including dams, reservoirs and weirs? What are the potential ecological roles within the hydrological cycle of flow-regulating structures in surface water bodies? What are the implications for water resources management?

Inevitably, the construction and operation of a dam or any other flow-regulation structure in a river, exerts a series of positive and negative effects on both upstream and downstream sections of the river. The transformation of a previously riverine environment into a lacustrine environment upstream of a flow control structure, results in a wide array of physical, chemical and biological changes. This transforms the structure, composition and functional attributes of biological populations, and sets in place a series of larger, landscape-scale changes that affect the ecological integrity of the entire river system. Little attention has been paid to the now "restricted" populations of organisms that are confined to the river reaches upstream of the flow regulation structure.

Whilst the original objective underlying the decision to construct the flow-regulation structure may have centred on the provision of assured water supplies for off-channel use, the resultant ecological changes have often been overlooked, or ignored, or considered to be of lesser importance. Inevitably, the potential social and economic benefits are considered to be of greater value than the likely ecological costs. Mitigation efforts have centred on the derivation of appropriate reservoir operating rules in attempts to provide sufficient water to sustain downstream riverine ecosystems. These have also been supplemented by catchment management actions designed to minimize sediment accumulation within the reservoir, and provide a high assurance of water yields that may be abstracted from the reservoir. Additional concerns relate to the ability of flow-regulating structures to release sufficient quantities and qualities of water to meet the needs of the Reserve and, in some cases, international obligations in shared river systems. From a conservation perspective, the presence of a new "artificial" ecosystem (the reservoir) poses important philosophical questions around the validity and desirability of attempts to protect the original riverine organisms that are now restricted to a new lacustrine environment.

16. How does the current and emerging suite of WRM indicators reflect the dimensions (structure, composition and function) and scales (genetic to landscape) of biodiversity? What would be the characteristics of appropriate indicators for WRM that properly reflect all the dimensions and scales of biodiversity?

At present, South Africa possesses very few water resource management (WRM) indicators that provide insights into the structural, compositional and functional aspects of biodiversity. Instead, most WRM indicators reflect the availability and (seasonal and inter-annual) variability of water flows, the variety of different aquatic organisms present in a river system and the presence or absence of key indicator species, the state and condition of the riparian zone, and the presence (or absence) of water quality problems as indicated by alterations to chemical features of a river system. Clearly, this situation is inadequate for a reliable assessment of the different scales and dimensions of biodiversity, and also hampers sensible decision-making.

The Water Research Commission has recognized this arena as a high priority and has commissioned a detailed position paper on this topic. The position paper will identify the current "state of the art", examine possible shortcomings in current approaches, and propose appropriate new research that will address these inadequacies.

Programme 3: Impact and management of introduced species

17. What are the potential impacts on water resources of the widespread or commercial introduction of Genetically Modified Organisms (GMOs) into the environment, and what are the implications for policy and regulation of GMOs?

It is now widely recognized that the term "genetically modified organism" (GMO) in reality consists of two major classes of organisms, namely:

- *Genetically modified organisms,* where a physiological or biochemical

intervention has been performed on an organism to change, alter or modify its genetic character to a point where it is genetically distinct (i.e. different) from the original (parent) organism, endowing it with the ability to exist under certain (different) circumstances, or to increase its ability to produce desirable characteristics or products; and

- *Genetically enhanced organisms*, where a physiological or biochemical intervention has been made that does not alter the organism's basic genetic make-up, (i.e. it is considered to be a variety of the parent organism, rather than genetically distinct from the parent organism), but rather seeks to improve or increase one or more of its existing attributes, such as its ability to produce larger crop yields, synchronize its production of seeds, fix atmospheric nitrogen or other desirable properties.

Whilst these differences may appear to be slight, they represent quite dramatic differences in terms of their "acceptance" or "desirability" amongst stakeholders.

To date, The Water Research Commission has not funded any research in the arena of genetically modified organisms – possibly because most genetically modified organisms are associated with terrestrial activities – such as food security, rather than the water sector. Nevertheless, these organisms have both direct and indirect implications for the water sector, for example through their water requirements and through the possible entry of genetically modified organisms into the riparian zones of rivers. Typical cases would be the accidental (or deliberate) release into riparian zones of new varieties of trees grown for wood and paper production, as well as new varieties of crop plants. In this type of situation, these organisms could become regarded as "super weeds" that could threaten the biological integrity of riparian and aquatic ecosystems. Their requirements for nitrogen, phosphorus or other nutrients would alter patterns of nutrient availability and exert additional restrictions on the indigenous species present.

Several concerns have been expressed about the adverse consequences of using genetically modified organisms; these range from moral and ethical considerations through to ecological, physiological and economic matters. The complex nature of these concerns means that their proponents will not be easily placated by traditional, purely scientific approaches. Instead, resolution of conflicting standpoints will require stakeholders to engage in participative processes, where clear and unambiguous scientific evidence can be provided to assist with decision-making. The Water Research Commission can play a leading role within the water sector by enabling and co-ordinating research efforts that are designed to provide unequivocal evidence on the water-related aspects of these organisms the debate. In turn, this will assist national authorities (e.g. the Department of Agriculture), that are charged with the primary responsibility for developing and implementing policy instruments related to the use of genetically modified organisms in South Africa.

18. What is the extent and potential impact of nuisance species (terrestrial and aquatic; fauna and flora; alien and indigenous) on environmental functioning within the hydrological cycle?

Whilst a considerable volume of research has been conducted on invasive alien and indigenous organisms over the last 35 years, the Water Research

Commission has focussed it's funding strictly on those issues that have direct relevance for water resource management. One of the major concerns related to the numerous different research projects that have been conducted on behalf of several different funding agencies, is that there appears to be a relatively limited degree of co-ordination between the various funding bodies. This has, in some cases, hampered proper consolidation and integration of national efforts to control invasive species and reduce their effects on the country's terrestrial and aquatic ecosystems.

This situation can be resolved by conducting a thorough overview of all efforts directed at or linked to invasive species, followed by a clear prioritisation of key issues of concern. This could then form the foundation for improved national strategy and policy, as well as a basis for enhancing collaboration between the different funding agencies and research teams. Here, the Water Research Commission could play a pivotal leadership role within the water sector, acting as a knowledge broker. This would also help to improve the transfer of knowledge and technologies across South Africa as well as to our SADC neighbours.

Programme 4: Interfaces

19. What is the contribution of freshwater, derived from land, but not delivered through river mouths or estuaries, to the nearshore marine zone? What is the ecological significance of this contribution? What are the implications for water resources management?

In South Africa, very little research has been directed towards understanding and quantifying the freshwater contribution that enters near-shore marine zones as a result of direct (groundwater) flows from the terrestrial areas located between river mouths and estuaries. This freshwater contribution is particularly important in the higher rainfall (equatorial) regions of Central and West Africa, and may also be important along the wetter south-eastern coastal zone of South Africa. Some research has been conducted to evaluate the extent and significance of freshwater contributions from river mouths and estuaries; this needs to be extended to improve our understanding of the extent and significance of groundwater contributions. In turn, this will help to improve our understanding of the water balance of coastal catchments and the implications of land-based activities for near-shore ecosystems, whilst also improving our ability to reduce the potentially adverse consequences of materials derived from terrestrial activities on sensitive coastal ecosystems.

20. What are the distribution and the current & projected utilisation of deep (>500m) groundwater bodies in South Africa? What are the potential impacts (geochemical, geohydrological, ecological) of deep (>500m) groundwater extraction on the components of the hydrological cycle, and on environmental functioning within the hydrological cycle? What are the implications for policy and regulation?

Deep groundwater resources are currently under-exploited as sources of water for human use in South Africa and very little information is available on the quantity, quality and reliable yield of these sources, upon which to base

management decisions. In turn, this prevents proper planning and also reduces opportunities for incorporating the water from these sources into the national water balance.

Future research is needed to understand the role of deep groundwater sources on the subterranean, terrestrial and aquatic components of the water cycle, and determine the extent to which these resources may be exploited sustainably. The associated implications that such exploitation patterns may have for groundwater-dependent ecosystems, or for the near-shore marine zone, also need to be evaluated. This will then form the basis for the development and implementation of appropriate policy instruments. Once again, the Water Research Commission can play a leading role in directing and co-ordination national research efforts in this arena. Ultimately, the Department of Water Affairs and Forestry, as custodian of all water resources in South Africa, will need to ensure that any exploitation of deep groundwater resources is regulated in an appropriate way.

21. To what extent do artificial recharge practices impact on biochemical, geochemical, hydrological and ecological processes within the hydrological cycle? What are the implications for policy and regulation?

Artificial recharge of aquifers offers an excellent opportunity to increase the safe yield of aquifers that are used to supply water for human uses, and to minimize adverse ecological consequences associated with high rates of groundwater abstraction form shallow aquifers. This is particularly relevant for many communities and farming operations located in the more arid regions of South Africa where there is a very high degree of reliance on groundwater. However, whilst aquifer recharge offers great promise in terms of increased quantities of water, we lack detailed knowledge of the precise geophysical and geochemical changes that occur as a result of aquifer recharge. This poses the risk that adverse chemical changes could render the water unfit for its intended use or impose a requirement for expensive treatment prior to use.

There is therefore a clear need for improved understanding of all the processes involved in or affected by artificial aquifer recharge attempts, as a basis for the development of appropriate policy instruments. The Water Research Commission is ideally placed to provide leadership in this research arena and facilitate the process of policy development in support of the Department of Water Affairs and Forestry.

22. What is the role of groundwater-dependent ecosystems (those contained within aquifers, as well as Karst and cave systems) in regulating ecological processes between components of the hydrological cycle?

Several research projects have been carried out on those terrestrial ecosystems that depend on shallow groundwater aquifers for their survival. These have focussed particularly on riparian vegetation and on estimations related to the quantity of water required by these ecosystem components. Very little emphasis has been placed on the geochemical aspects of these waters, other than the type,

degree and spatial extent of contamination that might occur as a result of inappropriate land-based waste disposal activities.

Shallow groundwater aquifers also play critically important roles in sustaining the base flow of river systems during the dry months of the year when no rainfall occurs. Any deterioration in either (or both) the quantity or quality of these groundwater sources will have highly significant consequences for dry season surface water flows in river systems. Here, the quality aspects of groundwater contributions to baseflow are also critically important in terms of the degree to which dry season flows remain fit for human use. Contamination of baseflow by agricultural return flows or other forms of wastewater pose significant challenges for water resource managers.

In addition, shallow groundwater aquifers are often the only source of water able to sustain riparian vegetation along seasonal and ephemeral rivers in the arid regions of southern Africa. These shallow aquifers are normally recharged during the infrequent rainfall and resultant runoff events that characterize these regions. If some or all of this runoff is intercepted and then recharged to deeper aquifers, shallow aquifers that rely on local runoff for their recharge will become progressively desiccated and unable to supply the water requirements of their riparian vegetation. In turn, this will hamper the sustainable management of these seasonal and ephemeral river systems.

The Water Research Commission is ideally placed to provide a strong leadership role for the water sector in this research arena, and to support national policy development efforts.

Programme 5: Resource directed measure (RDM)

23. What are the implications of climate change for the philosophical basis of in-stream flow requirements (IFRs) of aquatic ecosystems and the Reserve, the methodologies currently used to determine IFRs, and the status of existing environmental flow allocations? What are the options for policy responses?

The anticipated effects of global climate change could cause important changes to the hydrology of southern Africa and, if these occur as anticipated, they will likely affect every component of the hydrological cycle. If these changes do indeed occur, they will have important consequences for assessments of the quantities of water and patterns of flow that are required to sustain aquatic ecosystems as a central part of the "Reserve". In particular, if the flow patterns or hydrological characteristics of a river change as a result of climate change, this could alter the philosophical basis of in-stream flow requirement methodologies, as well as hampering the practical execution of such assessments for aquatic ecosystems. In turn, this would cast doubt on the applicability and relevance of the quantities of water recommended by those in-stream flow requirement studies that may have already been carried out in priority catchments.

If the above observations are indeed valid, there will be a need for careful evaluation of the underlying philosophy of in-stream flow requirement methodologies, followed by a clear policy level response that will guide current and future assessments of the flows required to sustain aquatic ecosystems. Once again, the Water Research Commission is ideally placed to play a strong leadership and co-ordinating role within the water sector; first by directing a

comprehensive review of the methodologies used, and then evaluating the likely consequences of potential climate change scenarios. This will enable the Department of Water Affairs and Forestry to develop an appropriate regulatory and policy response.

24. What are the strategic research issues and key knowledge gaps related to the derivation of in-stream water quality criteria for aquatic ecosystems (freshwater and estuarine)? How should these be addressed?

The original "trigger" for research in this arena was the emphasis placed on the development of water quality guidelines for freshwater aquatic ecosystems as part of the suite of water resource management "tools" being developed by the Department of Water Affairs and Forestry. At the time, this programme engaged a wide spectrum of aquatic scientists and researchers and culminated in the production of the first edition of South Africa's series of water quality guidelines. Since then, however, interest has tended to wane and few researchers are still active in this field, with very little new capacity being developed.

Originally, the water quality guidelines placed greatest emphasis on inorganic constituents and very little attention was paid to organic constituents. Given the appearance of growing numbers of novel organic compounds each year, it is also clear that our ability to undertake the necessary analyses for these substances is also declining or is constrained by the high costs of such analyses. Parallel attempts to circumvent these problems concentrated on the use of bioassay techniques that sought to use different types of toxicity assessment as criteria for acceptable or unacceptable levels of contamination in water. Whilst these efforts continue today, they too have been scaled down.

One of the most important gaps in knowledge is caused by the absence of water quality guidelines for estuaries. The available guidelines for freshwater systems and marine water quality guidelines are both inappropriate for use in estuaries. This has hampered our collective efforts to manage the water quality of South Africa's estuaries. The Water Research Commission occupies a leadership position within the water sector and would thus be the ideal organization to co-ordinate national research efforts that aim to consolidate our knowledge and assist with the development and implementation of appropriate national policy and regulatory instruments.

25. Current methods for determination of IFR take little or no account of important ecosystem processes related to the integrity, functioning and resilience of those systems (e.g. oxygenation, metal sequestration, nutrient cycling, sediment-water interactions and sediment quality). How should/could existing and emerging methodologies be adapted to integrate these aspects into IFR determinations?

Currently, in-stream flow requirement methodologies are based on simplified considerations of biodiversity that concentrate on the structural and (sometimes) compositional aspects of biodiversity. These tend to ignore important functional attributes of biodiversity with the result that key ecological processes are often not included, or are considered to be represented by some surrogate measure

linked to the presence or absence of key indicator species (see Issue 16). Whilst this is a pragmatic approach, it omits consideration of these key processes and consequently is unable to provide useful information on the degree of integrity, resilience or vulnerability of aquatic ecosystems to potential external changes. This is clearly an undesirable situation and needs to be remedied if estimates of ecological in-stream flow requirements are to have proper relevance in water resource management approaches.

The Water Research Commission has recently initiated a comprehensive review of current methodologies that are used as indicators of biodiversity in aquatic ecosystems, with the intention of using this as a foundation for the development of indicators that more fully reflect the structural, compositional and functional attributes of biodiversity. This review will pay particular attention to ecosystem-level processes that are needed to provide researchers and decision-makers with appropriate information on the extent to which aquatic ecosystems are able to continue to deliver the ecosystem services, goods and benefits that are needed of them.

WRC Strategic Issues

26. What are the potential impacts of national, regional and NEPAD poverty alleviation policies and strategies on the hydrological cycle, and hence on the availability, quality and reliability of water resources?

Virtually every research project initiated by the Water Research Commission can provide (or already has provided) some information that is relevant to this issue. However, there is no accepted country-wide assessment, or assessments directed at specific development nodes, that can provide unequivocal answers to all aspects of the questions posed above. This hampers South African efforts to provide fully appropriate leadership in SADC and NEPAD efforts to alleviate poverty and attain the Millennium Development Goals. The pressing need to implement poverty alleviation measures and improve the quality of life of previously disadvantaged peoples has often meant that the impacts of the remedial measures are ignored. Clearly, this situation is not sustainable in the long-term and decision-makers will increasingly need to deploy impact mitigation or rehabilitation strategies to prevent long-term degradation of the country's water resources.

Clear and unambiguous information is needed at a national scale, as well as at catchment scales, to understand the likely future trajectories of water supply and demand, as well as the consequences for the quality of these resources. Several catchments in South Africa are already approaching closure and "new" supplies of water are not easily available or economically affordable. It will also be important to understand the different supply-side and demand-side management options that will need to be deployed to meet the future needs for water on a sustainable basis. In particular, greater certainty is needed around our ability to predict the areas where new or expanded developments will occur, and when this will likely take place. In turn, this information will need to be incorporated into the country's longer-term planning process and used to derive appropriate water resource management strategies.

27. What are the implications of HIV/AIDS scenarios for water use and water resources management (quantity and quality)?

To date, the Water Research Commission has not funded any research into the implications of the South and southern African HIV/Aids pandemic for the quantity and quality of the country's water resources, or their management.

Other studies have provided initial evidence that the HIV/Aids pandemic has had, and will continue to have, extremely serious implications for the entire water sector and for water resources management throughout the SADC region. Amongst the typical implications are:

- People with compromised immune systems are also vulnerable to poor water quality and can more easily contract a wide variety of water-borne diseases if they are supplied with water of a sub-standard quality;
- Rural people who have to walk long distances to fetch water face increased risks of water deprivation if they are weakened by HIV and/or Aids – these individuals and their care givers will find it increasingly difficult to meet their daily water needs. Where these communities have to rely on water of uncertain or dubious quality, their plight is worsened;
- Inaccurate estimates of population numbers and population growth rates hamper proper planning of new water supply schemes – the time lag between initiating (conceptualising) and completing (commissioning) a large water supply scheme may mean that fewer people than anticipated will be present when the scheme comes on line. In turn, this will make it difficult to recover the costs of such schemes or to recover the costs of providing wholesome water supplies to communities;
- Since HIV/Aids tends to have greatest effects on the younger, more economically active and mobile members of the population, tending to spare the elderly and very young, the "survivors" may not be able to afford to pay for service delivery when such services are finally delivered.

It is important to note that a far wider suite of consequences than those listed above, is already occurring. The pressing urgency of the situation is reflecting in the enormous numbers estimated for HIV/Aids prevalence in several southern African countries. The Water Research Commission is ideally placed to lead and direct a national effort that would examine the available evidence and provide an unequivocal evaluation of the current and future situation of the pandemic, as well as firm policy recommendations for urgent implementation within the water sector. This would also contribute to the development of appropriate national and regional (SADC) policies and strategies.

7. DISCUSSION AND CONCLUSIONS

It is evident from the analysis of the research that falls within the scope of the *Environmental Functioning Within the Hydrological Cycle* thrust, that a large body of knowledge can be considered relevant and/or useful in answering the questions posed within the priority list of issues. The objective of this review was to evaluate the extent and depth of coverage of this body of research, and to identify gaps in our understanding of environmental functioning within the hydrological cycle. This will enable WRC research managers to identify those specific areas of research where much additional value can be gained from existing studies with little additional effort, and therefore for very little investment. This value can be obtained by:

- Integrating recent WRC research in the field, along with available information generated from other organisations, and presenting a strategic issues paper that: summarizes our best available knowledge, sets out the potential implications of current and projected scenarios, and indicates options for policy responses, or specific areas where policy or research responses will be needed;
- Commissioning highly-focused research projects to integrate and add value to existing knowledge, information and data, and thus deriving new insights to inform, define and refine possible strategic and policy responses; or
- Commissioning or stimulating new basic or applied research to address critical gaps in our knowledge around identified priority issues.

An example where value can be added to the existing body of knowledge would be to apply the knowledge gained from research that was focussed on a specific catchment or on a particular river, to another area of South Africa, to test the applicability and usefulness of the understanding gained of biophysical, biochemical and ecological processes and functioning in these other catchments and rivers.

When examining the results of the database, it is important to remember that this study only assessed the *quantity* of research carried out. In order to properly address each of the questions posed in the priority list of issues, high quality, focused research will be needed. This may require the presentation of "old knowledge" in new and innovative ways, or the initiation of new research programmes that address specific future problems. In some instances, syndicated research programmes funded by several organizations could contribute to meeting this need. However, whilst this is a technically and economically feasible option, most research-funding organizations appear to be reluctant to fund syndicated research programmes where their individual participation, or the component funded by them, may be difficult to distinguish from the contributions made by other funding agencies.

In addition, the rate at which situations, needs and problems change has resulted in a growing trend of research being conducted in response to a specific issue or problem, rather than in a proactive manner that addresses potential future issues. South Africa has consistently shown that it is somewhat better at responding to future issues than its SADC neighbours, but not better than its trading partners. This situation can lead to further problems in future, if no consideration is given to the impacts of these relationships on sustainable water resources management. A scenario-type analysis is needed within the WRC, where trends are constantly monitored to ensure that the Commission anticipates, and then responds promptly and appropriately, to future issues before they emerge as problems.

The role that the WRC plays in response to future issues also needs to be examined within the scope of its mandate. These boundaries are clearly illustrated by the fact that the hydrological cycle component that has received the most attention is the aquatic component. Almost all research into different aspects of the other components of the hydrological cycle are supported and/or funded by other agencies and institutions.

An additional benefit of this review was that it provided insights into the accessibility and usefulness of information sources that can and are being used by researchers to undertake literature reviews in a particular field. The process of developing the database therefore highlighted some limitations in

capturing a definitive list of all literature and projects that are important and relevant to the priority issues of the thrust under review.

The contents of the database were derived from existing electronic databases that are easily available to the researcher. The WRC publication list is available through internet access and requests for copies of WRC reports can be made through its Publications Centre in Pretoria. Out of print WRC publications can either be found in the WRC Archive library or in the National library in Pretoria. The National Inquiry Service Centre (NISC) database is widely espoused as being the most comprehensive collection of databases which covers a wide range of topics. NISC SA includes the Water Resources Worldwide database which was used in phase 2 of this study to determine which publications from DWAF were relevant to the domain. The Water Resources Worldwide database contains over half a million indexed citations from 1970 to present.

It became evident in phase 2 of this study that there were gaps in the DWAF publication search results using the NISC database; these included the majority of the large catchment studies that were undertaken in the 1980s and 1990s. A newcomer to the field of water resources research would be unaware that these gaps exist if relying on the database to provide a comprehensive list of all research relevant to their area of interest when undertaking a literature review. These gaps in electronic databases are generally 'filled' by personal networks. Personal networking is a valuable mechanism of finding literature that is not readily available or identifying the existence of research that has been undertaken in the past and has been lost from institutional memory or not captured in an electronic database. The mechanism is however vulnerable due to factors such as the lack of resources and mobility of researchers which could undermine the effectiveness of this mechanism to fill the gap.

Due to the nature of the research undertaken in the water resources management field, many organisations are conducting research that focuses on the different hydrological cycle components and are at different levels (situation based; process or policy related research) or at different scales (global through to site specific studies). Because of this multiplicity and complexity, no one organisation takes the responsibility of capturing all the research that has been undertaken in the past. The result of the lack of a central archive is the 'loss' of some research to the general pool of knowledge, especially older research that still needs to be captured by existing databases. The knock-on effects of this 'loss' is that research efforts in some fields are being repeated and in some cases 'old' research is discounted as no longer being valid. The danger of this is that no progress is made through the research cycle. There is a natural progression of research effort from basic research to applied research to policy research, which in turn is (sometimes) implemented and then should feed back into the research cycle by identifying and directing the focus of improved basic research. The result of this lack of access to 'old' research is that we get stuck at one stage in this cycle and don't progress; resulting in the same research being undertaken by the next generation of scientists in a particular field.

An additional issue relates to the changing emphasis or focus of research efforts as 'new' priority issues require attention. This has resulted in many researchers moving from one arena of research to another whilst still other researchers remain within a specific field of investigation. Overall, this has resulted in a succession of research fields being investigated, though the overall research effort has in many cases been 'diluted' because of the relative scarcity of researchers with detailed knowledge of specific areas of interest (**Figure 39**). In some cases, the movement of researchers from one field to another 'emerging' or favoured topic has reduced the critical mass of the remaining researchers to a point where it is difficult for them to conduct sufficiently detailed studies. The proliferation of research areas has also diminished the funding available to be spent on research in many areas, causing further problems. In several cases, researchers have returned to a particular field of study, often after several years, when specific problems have needed to be resolved.

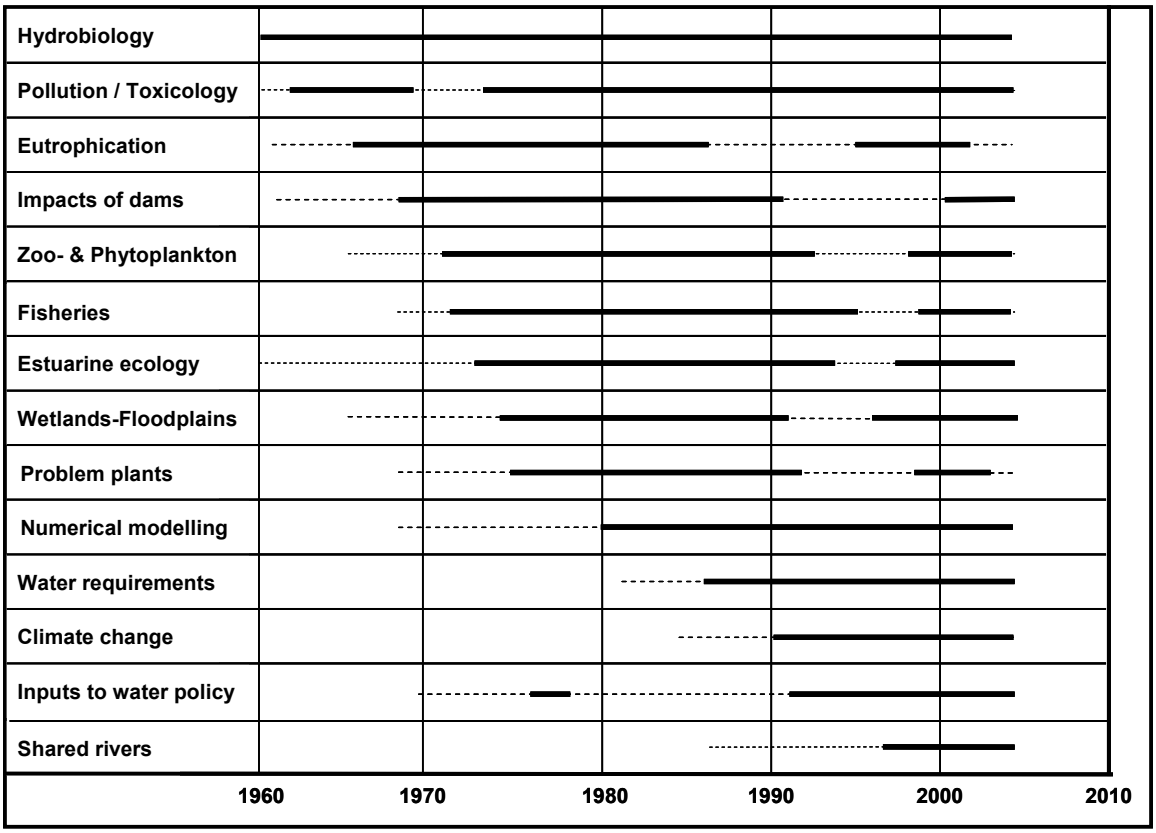

Figure 39. Diagram showing the chronological sequence of key research areas in South Africa. [Solid lines indicate continued periods of high-intensity research; dashed lines indicate periods of initial exploratory research or non-co-ordinated research with few researchers engaged in the specific research field. (Diagram redrawn from Ashton, 2004).

It is also important to recognize that the context and content of the research cycle is heavily influenced by prevailing social, political and economic factors that are, in turn, constantly changing their emphasis and direction. This has a significant influence both on the scope of the crosscutting domain and the questions that guide the research that is undertaken within the thrust. The dynamic nature of these external drivers that determine priority issues and areas of research within the WRC is illustrated by the presence of a large number of research records relevant to some issues, and an absence of research records for others. However, it must also be borne in mind that this does not mean that some issues do not require further research, or that no relevant information exists for other issues. It simply means that, in some instances, existing research needs to be integrated or examined from a different perspective in order to add value, or that new research initiatives need to be investigated and consortiums established to address those issues where the WRC provides a supporting role rather than a leadership role.

There is also a natural progression in the development and growth of a body of knowledge that is illustrated conceptually in **Figure 40.** As one progresses up a metaphorical staircase from observation and measurement to knowledge and, ultimately, through intelligence to wisdom, the ability to provide vision and leadership in a particular field increases. The steps of understanding and wisdom are the ones where the most value is added to fulfil society's needs. The existing body of knowledge, as it relates to this review of the WRC domain, relates primarily to the initial steps in the knowledge staircase. Considerable additional value can be added by focussing new research to build on existing research in order to progress to the 'understanding' and 'wisdom' steps in the staircase. These steps would add new value to decision-making, policy, and management related research that should focus on regional and/or strategic research. Centres of excellence that focus on specific priority needs are useful mechanisms to elevate research to a level where it generates understanding and wisdom.

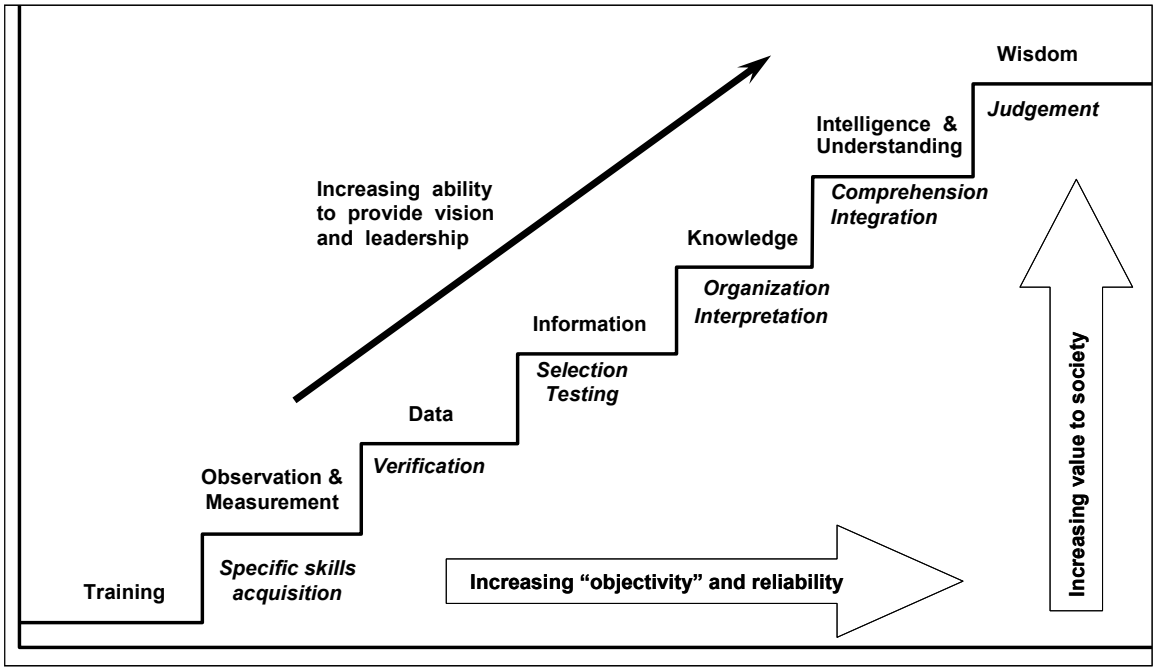

Figure 40. Conceptual diagram illustrating the progressive increase in the types of skills needed (italicized text at vertical risers) to achieve specific outcomes in terms of the increasing value of data through information and intelligence to wisdom. (Figure redrawn from Ashton, 2005).

The real impact of research, in terms of adding value or progressing up the 'staircase', is difficult to measure. Tracking the benefits of research through the research cycle is particularly problematic since there are often long lag times before tangible benefits are realised or recognised. This can be seen, for example, in the time taken for the results of eutrophication research to be incorporated into policy, and the long delays experienced in the implementation of in-stream flow requirements in specific river systems. The social impact of some forms of research can be estimated by the magnitude of improvement in the quality of life of the relevant people affected by the research – for example, people who receive water supplies and/or sanitation systems. However, this approach is not always easy to achieve and this is made more difficult by the lag times between completion of research and the implementation of specific management responses. An important additional point relates to the difficulties that have been experienced in "legitimizing" some of the scientific information derived from research information. Research findings are seldom accepted without their having passed through an extensive process of examination and verification by stakeholders and decision-makers. Only once this has happened is the "new" information likely to be adopted or used to extend or replace the "older", more deeply entrenched existing information. In some cases, the value of research may also not be recognised for some very practical reasons, one being that many reports and articles are not obtainable in a suitable format, or the contents of such documents are presented in an extremely 'dense' technical format that is very difficult to interpret and evaluate. During the course of this review it became evident that copies of 'older' research reports were difficult or impossible to locate and obtain.

The concentration of knowledge in researchers versus in knowledge management systems is an issue that also needs to be carefully reviewed. Both have their pros and cons. One solution would be to ensure that there are defined succession plans in place in the field of water sciences where young researchers are groomed in the knowledge that is available within their particular field by an experienced mentor. Succession planning would also help to ensure that the continuity of knowledge is maintained and that research can be elevated to a level where its value is clearly recognised, understood and utilized.

8. RECOMMENDATIONS

It is important to recognise that this review has focused only on Thrust 1 *Environmental Functioning Within the Hydrological Cycle* within the Crosscutting Domain *Water and the Environment*. A similar review has been conducted for Thrust 2 of the domain, which focuses on *Environmental Governance Systems* (Pegasys, 2005). These two reviews will feed information back into the domain's draft investment strategy (MacKay et al., 2004) and will help to determine those research issues that need to be prioritised for future investment. In addition, the results obtained from these two reviews need to be combined and analysed in accordance with the objective of this domain, which is to contribute to achieving a situation where our governance systems and our understanding of environmental processes and functioning are aligned to support sustainable water resources management that meets the needs of society.

This review provided useful insights into the contributions made by the WRC and DWAF to the body of research that is relevant to the domain for the last 30 years in terms of:

- The spatial distribution of research undertaken within South Africa;
- The scale of the research (i.e. research undertaken at regional, national, catchment or site specific scales);
- The level of research (i.e. research the has focused on situation assessments, process or policy related research);
- The temporal change in the focus of the level of research; and
- The relationship of research undertaken to the WRC priority issues and to components of the hydrological cycle.

In order to fulfil the primary objective of this review, it is recommended that the database and review process be expanded to include relevant research findings from other institutions. This will extend the insights gained from this review to a much broader and more comprehensive overview of the research funded by the entire water sector, and into the research focus of specific other institutions. The primary value to be gained by expanding the scope of the review would be accrued by the WRC and other research institutions; this would occur through the identification of key areas for potential collaboration, and recognition of opportunities to avoid duplication of research and investment. In addition, such an expanded review would enable information needs to be identified, confirmed and prioritized; these could include gaps in the knowledge base or a halt in the progression of research from basic research, to applied research, to policy research. These insights would help to improve the management of our national water resources and make a meaningful contribution to people's lives.

It is also recommended that this review be extended to include other Cross-cutting Domains and Key Strategic Areas (KSAs) within the WRC. A review of this nature would enable the WRC to take a strategic, futures-based standpoint in the determination of its investment priorities, enabling the organisation to focus on its mandate of achieving the aims and objectives of the National Water Act (Act No. 36 of 1998).

In order to address the issues surrounding the lack of a central archive or information database of research reports and products in the water sector in South Africa, it is strongly recommended that the WRC continue to invest in the maintenance of an information management system that records reference details of publications that are relevant to its core mandate and the scope of the various KSAs and Cross-cutting Domains.

In addition, the WRC should continue to strengthen the national water research effort by increasing the level of its support for specific Centres of Excellence. Assured sources of longer-term funding are essential if a research institution is to conduct meaningful, strategically important research. Also important would be a need to support and strengthen efforts aimed at growing and enhancing the skills and abilities of the national water research force. In particular, a focus on specific Centres of Excellence would also allow the WRC to identify and nurture specific leadership elements and

institutions that would help to expand and transform South Africa's cadre of water researchers, increase the numbers of competent black researchers, and meet the need for leadership and management skills in the water sector.

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APPENDIX A: DETAILED ANALYSIS OF EACH ISSUE

A1. Programme 1: Regional and global changes in the biophysical environment

Programme 1 comprises 12 issues, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

Programme 1 issues:
- Climate change and water resources availability;
- Climate change and background water quality;
- Climate change and nitrogen;
- Climate change and phosphorous;
- Climate change and water sharing agreements;
- Desertification;
- Implications of the Millennium Development Goals (MDGs) for water resources;
- Atmospheric emissions and their impact on water resources;
- Migration and urbanization impacts on water in the environment;
- Persistent organic pollutants;
- Radioactivity; and
- Persistent inorganic pollutants.

A.1.1 Issue 1: Climate change and water resources availability

The research question for issue 1 is:

"What are the implications of climate change for the amount, timing, variability, flow-related quality and assurance of water supply?"

The majority of research studies that are relevant to issue 1 have been conducted within the Kruger National Park in general and along the Sabie River in particular (**Figure A1**).

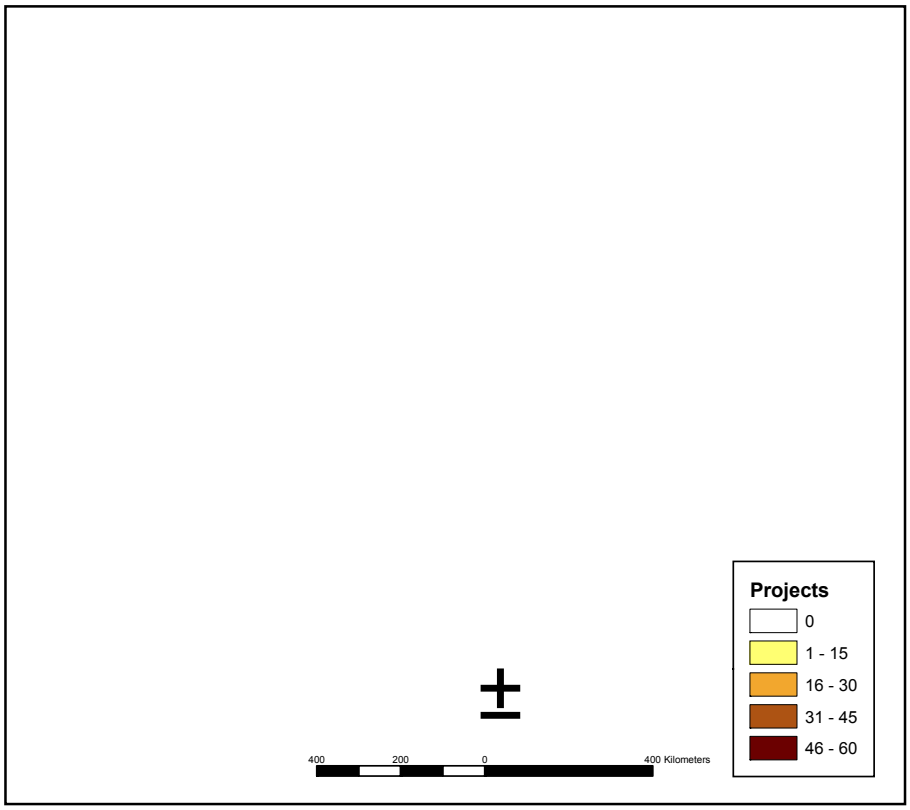


Figure A1: Tertiary catchment distribution of WRC research records relevant to issue 1 (n=79).

This research has focused on irrigation requirements and water use of crops, forestry and natural vegetation, and their impact on water resources. The understanding of river dynamics and hydraulics, and water balance processes, also comprised a large component of the research undertaken, where the focus was primarily process-orientated (**Figure A2**).

The majority of the research has been conducted at national and catchment scale, with the primary focus being on situation assessment and process orientated research (**Figure A2**). These studies include climatological modelling, rainfall estimation and forecasting, and rainfall stimulation studies.

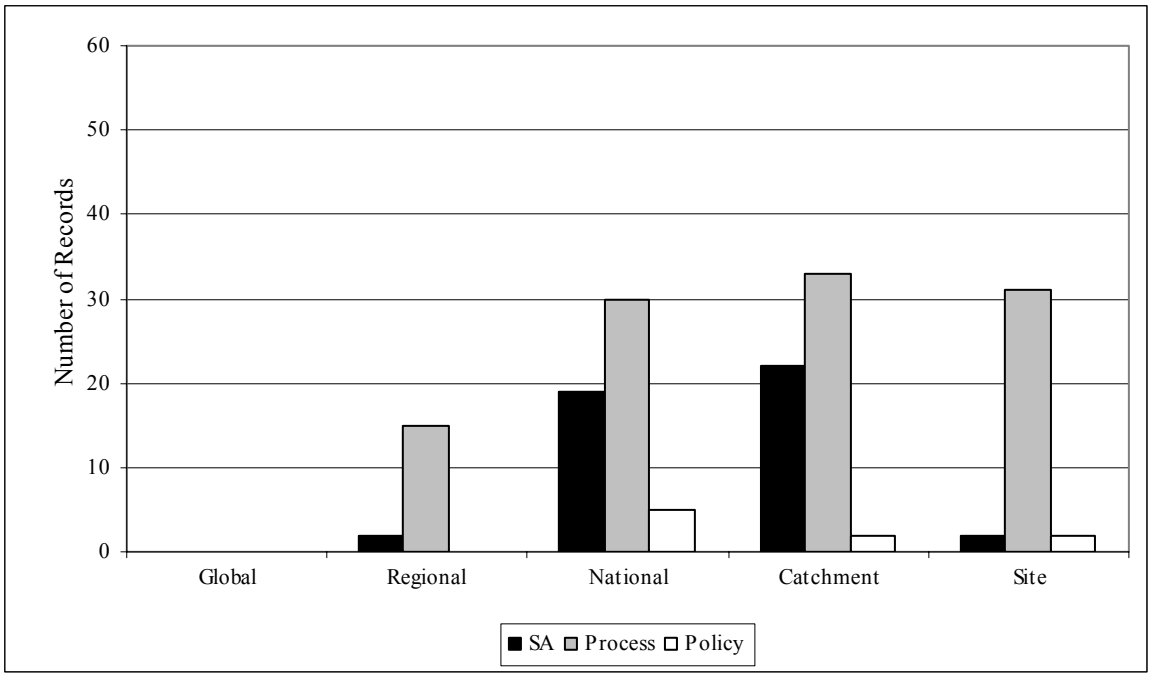


Figure A2: Number of WRC research records per level and scale of study relevant to issue 1 (n=150).

To date, the Water Research Commission has funded very little policy-level research related to climate change issues. Whilst it is clear that this issue has the potential for enormous ramifications at national, regional, continental and global scales, it is not strictly a water sector responsibility to drive national policy development in this field. It would be more appropriate for this issue to be led by the Department of Environment Affairs and Tourism (DEAT), since this department has the national mandate to drive national policy development related to climate change issues. Nevertheless, the insights, experience and knowledge contained within the water sector could provide important inputs to both national and regional policy formulation and should not be ignored. An important insight is that much of the international experience related to climate change issues has recognized that the potential consequences of global climate change have implications for both the blue and green water components of the hydrological cycle. Given the range, scale and potential implications of global climate change for southern Africa, South African research expertise has considerable potential to derive new insights into the green water components of the hydrological cycle in particular. In addition, there is a clear need for a comprehensive cross-sectoral policy response to climate change issues since there is incomplete evidence that climate change will indeed affect all aspects of the hydrological cycle. Here, it will be necessary to ensure that these efforts consider all the aspects of landuse that could potentially affect components of the hydrological cycle.

A.1.2 Issue 2: Climate change and background water quality

The research question for issue 2 is:

What are the implications of climate change scenarios for background water quality in South Africa's biogeoclimatic regions, and their consequences for water treatment technologies and policies, and in-stream water quality management policies and regulatory mechanisms?

The rivers that have been most researched in terms of information that could contribute to this issue are the Vaal, Harts, Modder, Riet and Orange rivers (**Figure A3**), as well as coastal WMAs and portions of the Limpopo and Olifants catchments.

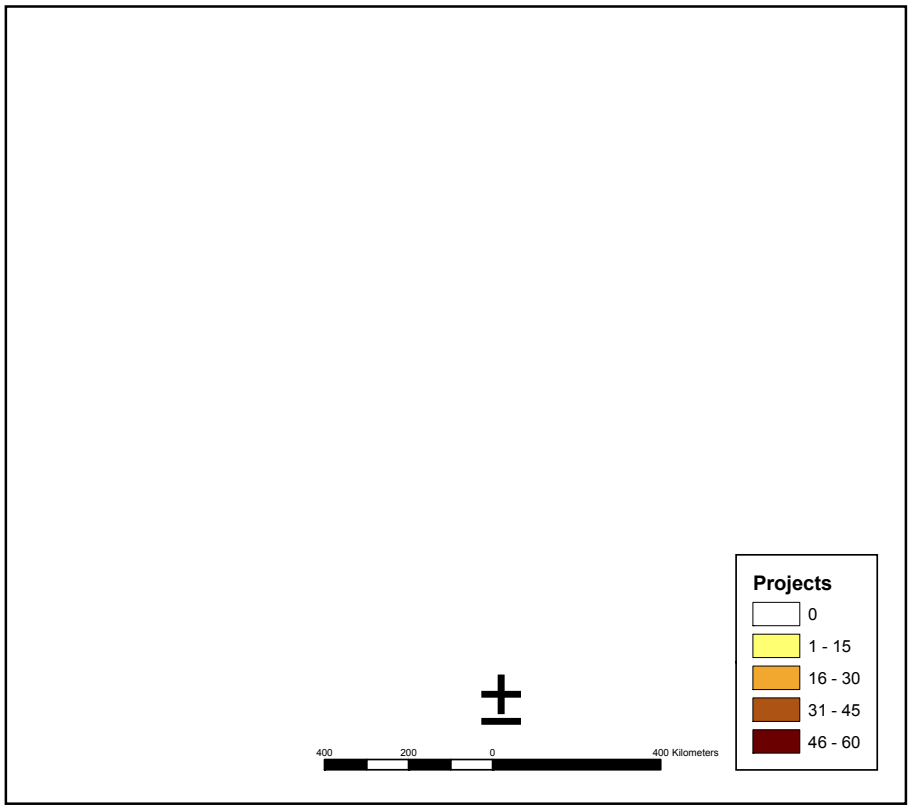


Figure A3: Tertiary catchment distribution of WRC research records relevant to issue 2 (n=64).

Most of the research that has been conducted has application at the national scale, and has focussed mainly on process orientated issues (**Figure A4**). Studies at a catchment scale have focused approximately equally on situation assessments and process research, while those projects that are site-specific are primarily process orientated. Policy related research has only been undertaken at a superficial level at a national scale. The focus of research that is relevant to this issue are: impacts of reduced water quality emanating from different landuse activities (e.g. agriculture, settlements, mines and industry) on receiving water resources; waste water and its treatment; and water quality modelling and pollution and their effects on river health.

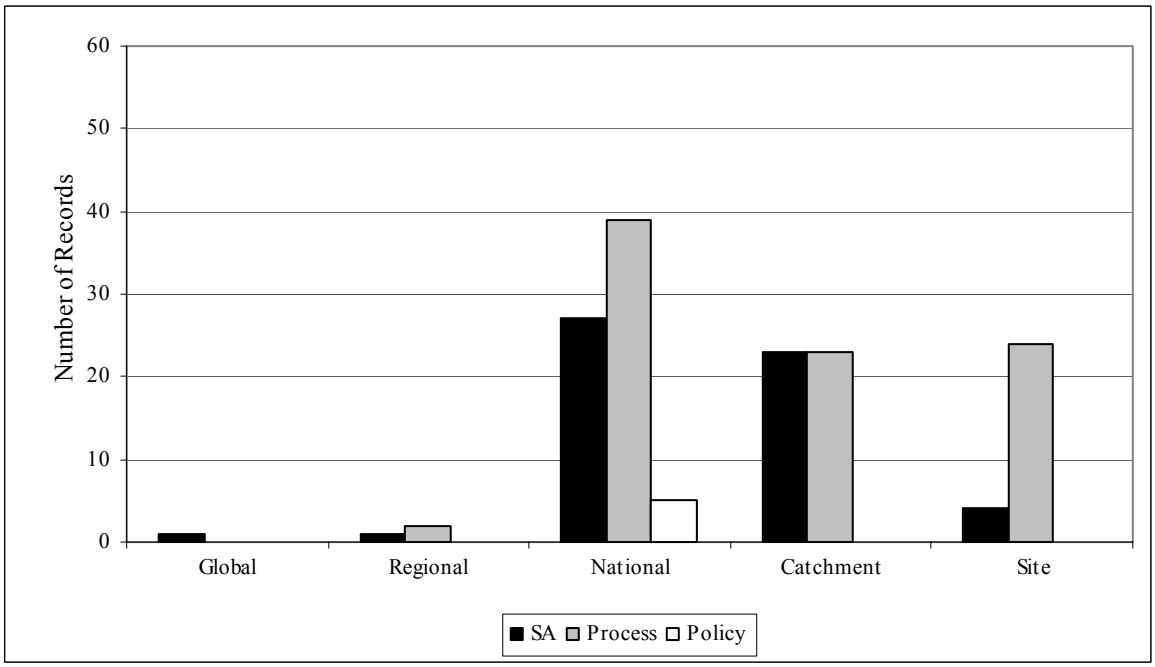


Figure A4: Number of WRC research records per level and scale of study relevant to issue 2 (n=141).

At first sight, much of the information that is available would appear to be indirectly related to this issue of concern. However, because much of the research has been process-orientated, the findings often have a far wider application that the original study site where the research was undertaken. Once again, national policy-level research should fall within the mandate of the Department of Environment Affairs and Tourism, with water sector contributions providing enhanced insights that could shape specific decisions. Nevertheless, the Water Research Commission can play a leading role within the water sector by assisting with the development of water-related policy that deals with the water quality implications of potential climate change scenarios.

A.1.3 Issue 3: Climate change and nitrogen

The research question for issue 3 is:

What are the potential impacts of global and regional climate change on nitrogen cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?

Most of the WRC-funded research that is pertinent to this issue has been carried out along the Vaal, Harts, Modder, Riet, Orange, Sabie and Olifants rivers (**Figure A5**).

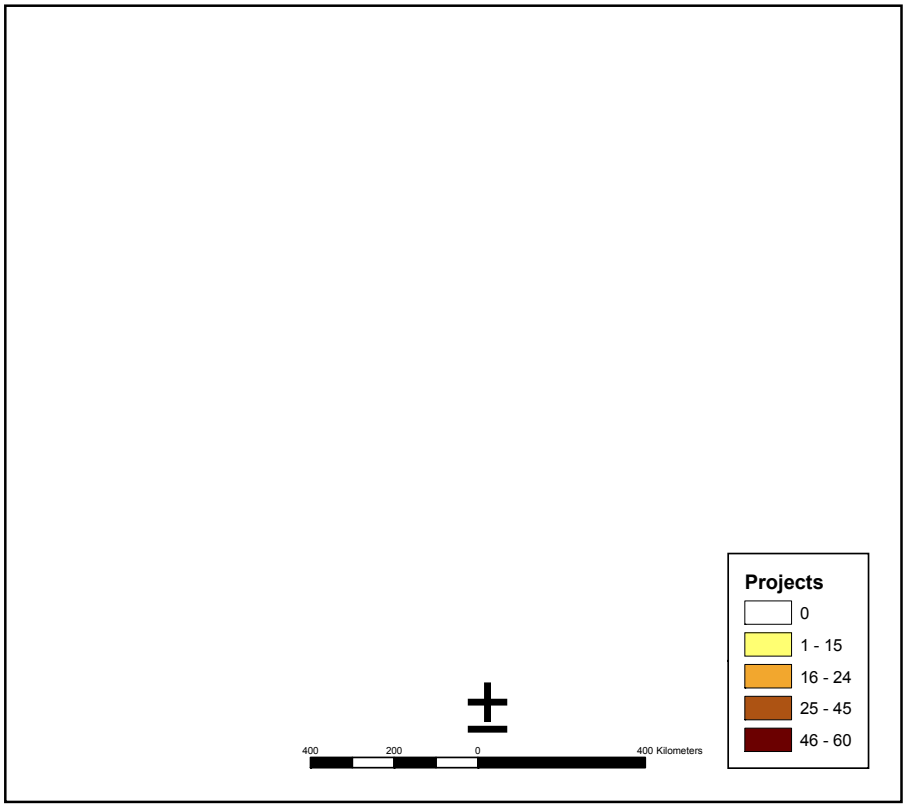


Figure A5: Tertiary catchment distribution of WRC research records relevant to issue 3 (n=13).

Whilst very little of the research that has been undertaken to date bears direct relevance to this issue, studies on the influence of nitrogen levels on crops, crop productivity, nitrates in groundwater and water quality studies in general, all provide background information that is relevant. Most of the research that has been undertaken has been at a process level, although a few national scale situation assessment studies have provided extremely important information (**Figure A6**).

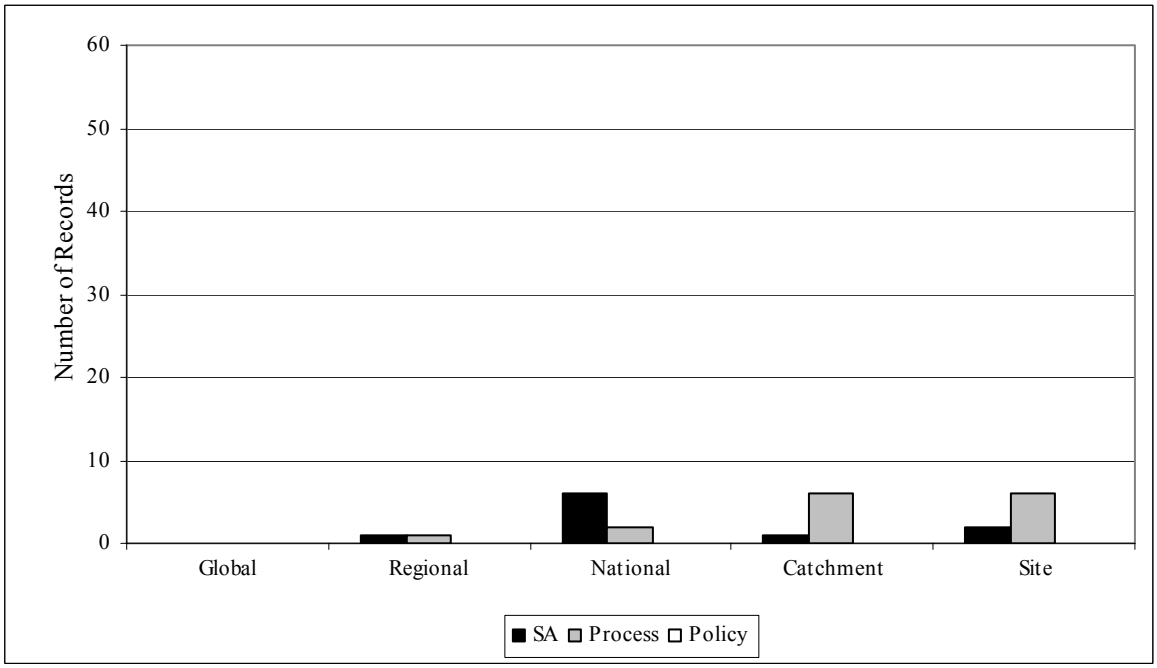


Figure A6: Number of WRC research records per level and scale of study relevant to issue 3 (n=24).

Much of the original research emphasis that was placed on nitrogen cycling processes was linked to, or associated with, the investigations into eutrophication processes that dominated aquatic research in the 1970s and early 1980s. Important eutrophication research findings demonstrated that most natural (unmodified) African waters are deficient in both nitrogen and phosphorus, though natural processes of biological nitrogen fixation could soon replenish nitrogen stocks required by aquatic organisms. Therefore, interventions designed to reduce the availability of nitrogen for aquatic organisms seldom offered practical solutions to eutrophication problems. Instead, phosphorus was identified as the critically limiting nutrient for the (nuisance) growth of algae and aquatic plants and the focus of most eutrophication research turned towards the development of strategies to reduce phosphorus inputs to aquatic ecosystems, and culminated in the promulgation of the 1 mg/litre concentration limit for total phosphorus in the Special Effluent Standard. Whilst this approach offered some relief from pervasively high levels of eutrophication, the "allowable" phosphorus limit of 1 mg/litre in effluents has had limited success in curbing eutrophication. Man-made reservoirs that receive treated effluent in their inflows have also been shown to be the sites for significant "sinks" for nitrogen. In some heavily enriched reservoirs, up to 50% of the inflowing total inorganic nitrogen load may be lost to the atmosphere through denitrification processes.

Much of the process-level information on nitrogen cycling has potentially useful applications in studies on the potential implications of climate change. In particular, the results of field and laboratory studies that related nitrogen cycling processes to prevailing water temperature dynamics can provide fundamental insights into the potential implications of climate change.

An additional important insight arising from research projects conducted on different aspects of the nitrogen cycle is that, despite being nitrogen deficient in relative terms, the cumulative total loads of nitrogen in river systems appears to have increased over time and resulted in increased nitrogen loadings to the near-shore marine zone. If correct, this has great significance for the ecological functioning of sensitive estuarine and coastal systems.

A.1.4 Issue 4: Climate change and phosphorous

The research question for issue 4 is:

What are the potential impacts of global and regional climate change on phosphorus cycling processes and rates in the hydrological cycle (including the atmospheric, terrestrial, marine, surface water and subterranean components of the hydrological cycle), as well as the potential implications for water resources management, and policy options for coping with possible scenarios of change?

The majority of the WRC-funded studies that are relevant to issue 4 have been undertaken along the Vaal, Harts, Modder, Riet, Orange, Sabie and Olifants rivers (**Figure A7**).

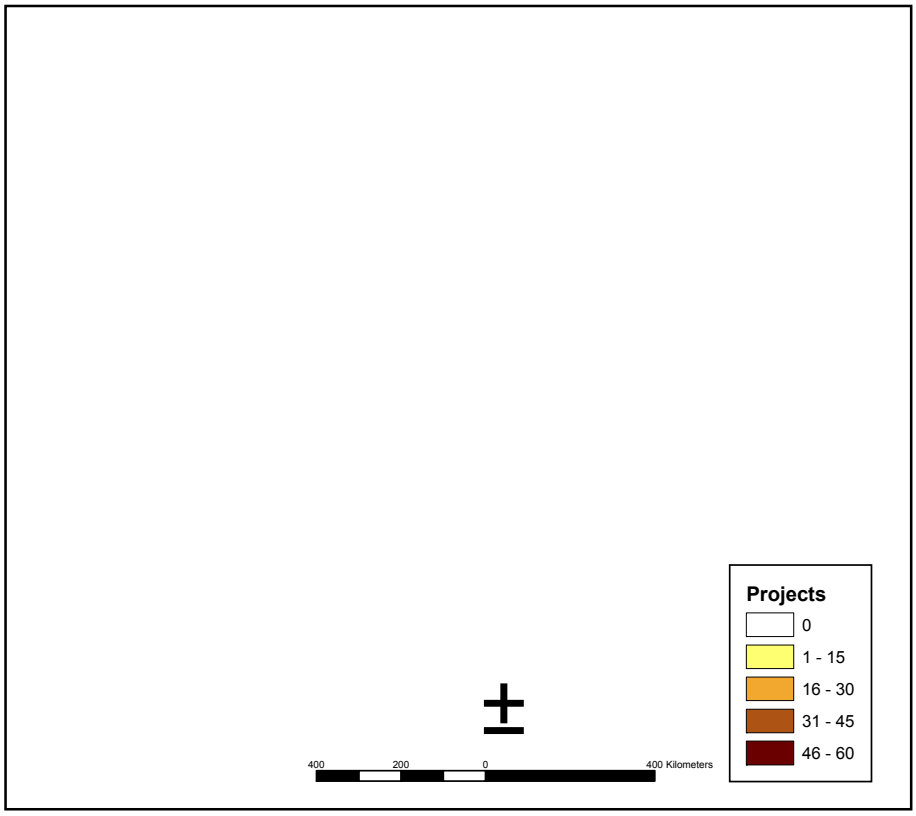


Figure A7: Tertiary catchment distribution of WRC research records relevant to issue 4 (n=11).

Research has been conducted at all scales of study except global (**Figure A8**), while that research that has been undertaken is very scarce. A total 33 studies have been undertaken to date. The focus of this research has been on pesticide use, algal blooms and phosphate concentrations, as well as phosphate removal in the water treatment process. Those studies at a national scale have focused primarily on modelling phosphorous loads in South African catchments.

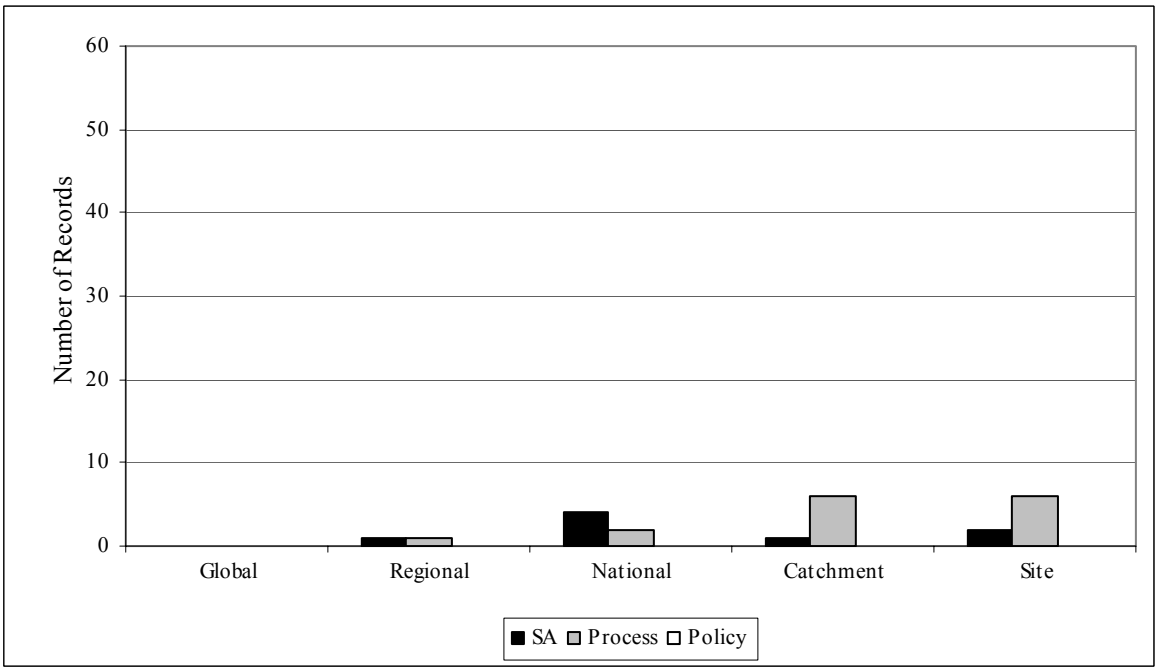


Figure A8: Number of WRC research records per level and scale of study relevant to issue 4 (n=19).

Interestingly, much of the research capacity that was originally developed during research projects aimed at understanding the phosphorus cycle in freshwater ecosystems (eutrophication studies in rivers and reservoirs), was later focussed on studies of the potential of wetland ecosystems as passive and active phosphorus removal systems to remove phosphorus from effluents. Much of this research emphasis was subsequently transferred to studies of the in-stream flow requirements of a variety of aquatic organisms that occupy different aquatic habitats (e.g. rivers, lakes, pans, reservoirs, wetlands), as well as large-scale catchment studies. In most of these cases, relatively limited attention was paid to issues of phosphorus cycling, because of the continued failure to convince water resource managers that the Special Phosphorus Standard of 1 mg/litre was too high, and should be lowered to approximately 0.1 mg/litre as a matter of urgency. Consequently, eutrophication issues that centre on phosphorus cycling processes remain a key concern to this day.

The few field and laboratory studies on phosphorus cycling processes in aquatic ecosystems have direct relevance for evaluations of potential implications of climate change on phosphorus cycling in all components of the hydrological cycle. The bulk of the recent research has been aimed at phosphorus removal or inactivation processes in conventional and novel water treatment systems, rather than on the fate and transport of phosphorus in aquatic ecosystems.

A.1.5 Issue 5: Climate change and water sharing agreements

The research question for issue 5 is:

What are the implications of climate change for existing and new water sharing agreements?

Those research projects that have the most bearing on the implications of climate change on water sharing agreements have been undertaken along the Orange and Vaal rivers, and within the Limpopo Province and the coastal catchments of South Africa (**Figure A9**).

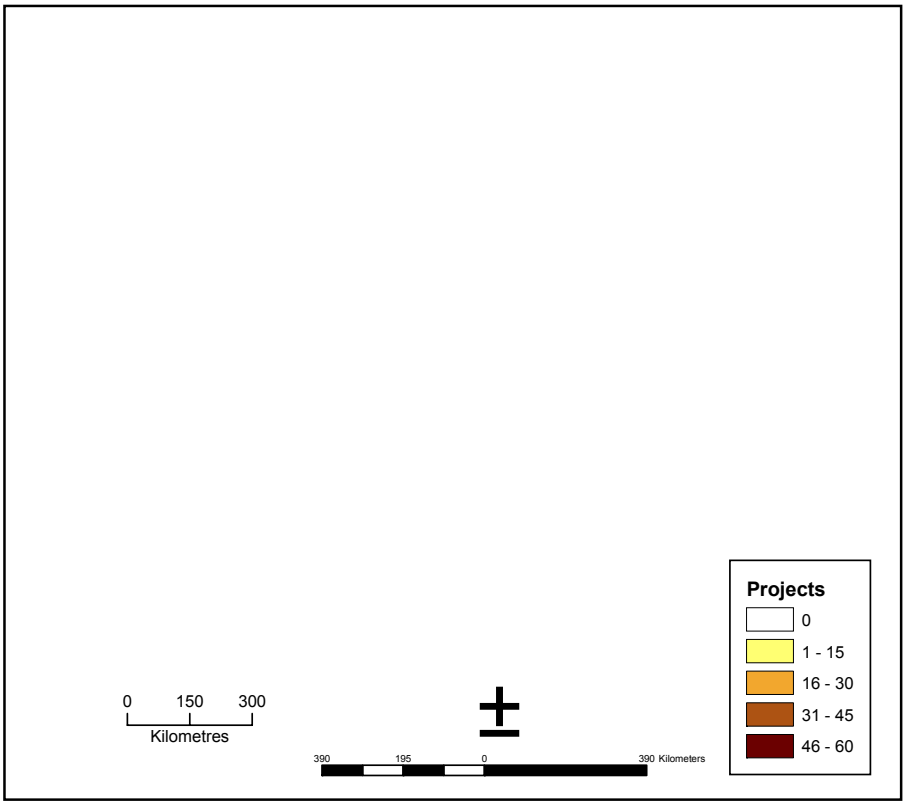


Figure A9: Tertiary catchment distribution of WRC research records relevant to issue 5 (n=29).

National and catchment scale studies dominate, with situation assessment level research being the most common type of research undertaken (**Figure A10**). Approximately equal numbers of policy related and process orientated research projects have been conducted, principally at national scale. There has been some research carried out on water resource planning, understanding water balance processes and water use efficiency, streamflow reduction estimations, and future climate system variability.

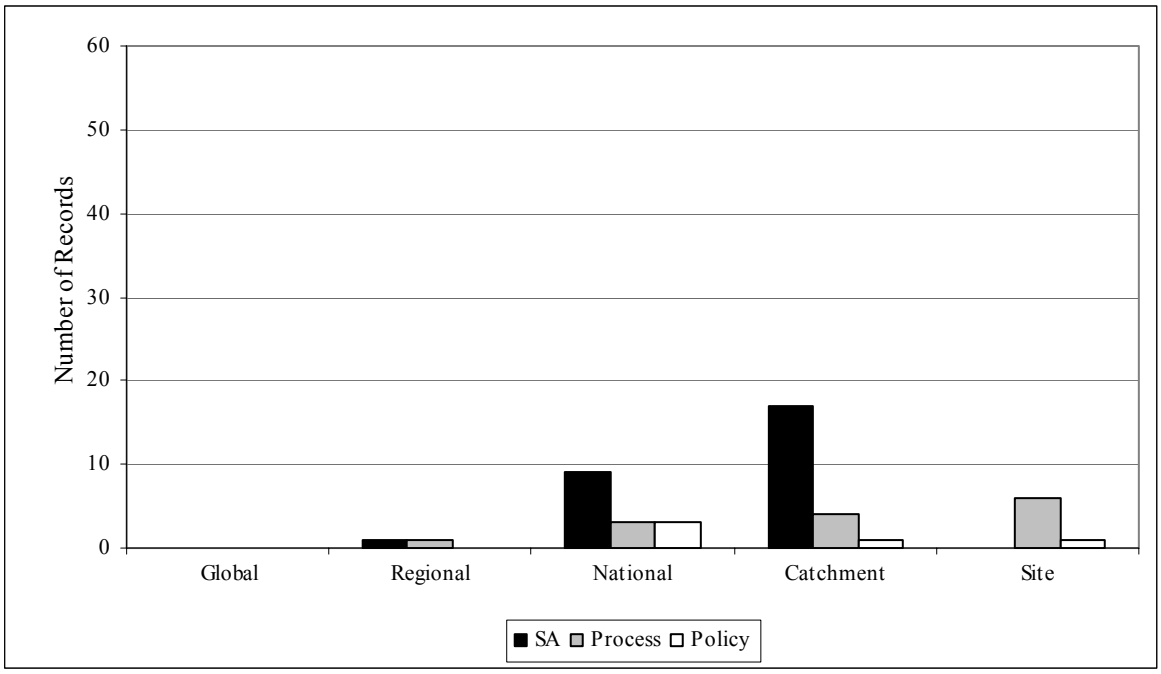


Figure A10: Number of WRC research records per level and scale of study relevant to issue 5 (n=39).

No research projects have been directed precisely at this research question, though several research programmes have provided useful insights that could form the basis for future research. In view of the increasing sensitivity around issues of inter-sectoral sharing of scarce water resources, and the equitable allocation of water between countries that share a common river basin, this issue is rapidly gaining international prominence and needs to be resolved.

A.1.6 Issue 6: Desertification

The research questions for issue 6 are:

What are the projected rates and patterns of desertification (caused by both climate change and land use practices), and their associated impacts on components of the hydrological cycle? What are the potential impacts of current and projected water use and management scenarios on desertification processes? What might be appropriate policy and regulatory responses?

Those tertiary catchments along the Orange, Vaal and Riet rivers and along the coastal regions of South Africa as well as sections of the Olifants and Crocodile primary catchments were those areas where the majority of the research projects relevant to this issue were undertaken (**Figure A11**).

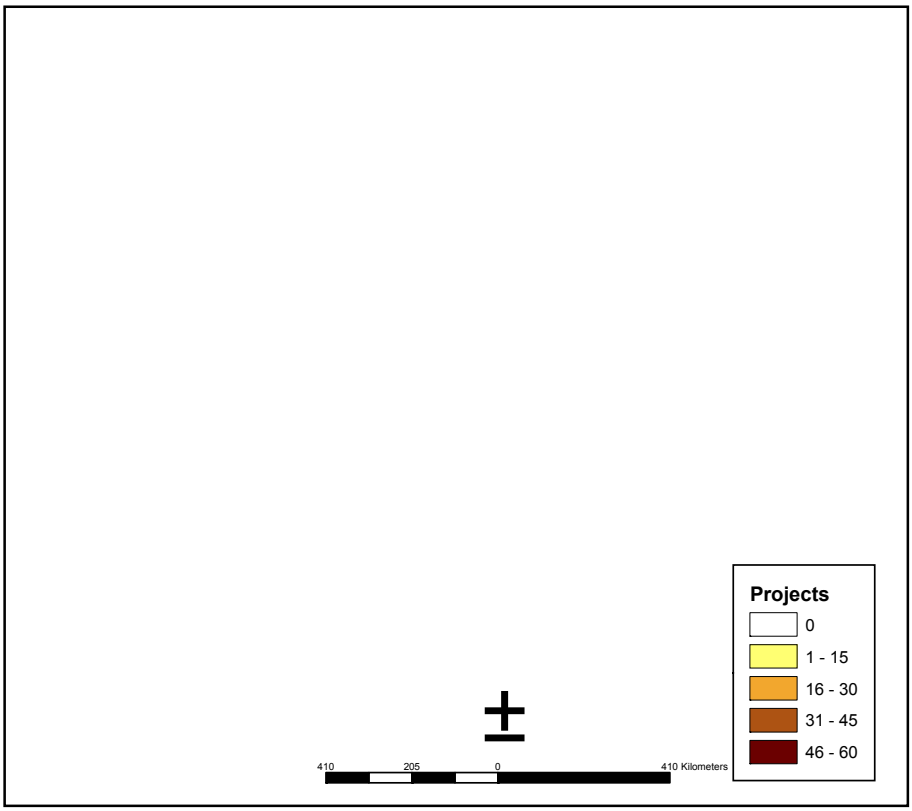


Figure A11: Tertiary catchment distribution of WRC research records relevant to issue 6 (n=50).

The majority of the research undertaken was at a catchment scale (**Figure A12**), where the focus was on water requirements for irrigation, long-term predictions from crop models, modelling water balance processes and understanding streamflow reduction activities. Situation assessment studies dominate on a regional and site-specific level, while at a national and catchment level the majority of the research conducted was process orientated. At the national and regional scale, the research focus was primarily on the occurrence and severity of droughts, rainfall stimulation and atmospheric water supply projects.

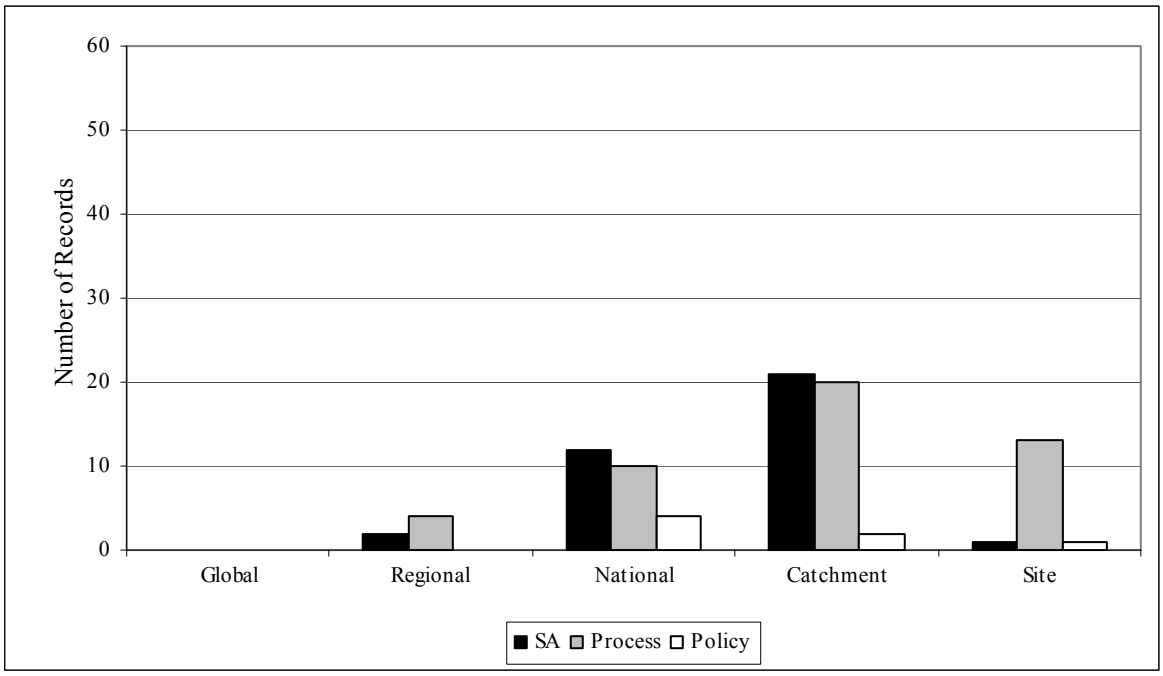


Figure A12: Number of WRC research records per level and scale of study relevant to issue 6 (n=77).

South Africa has ratified the United Nations Convention to Combat Desertification and this places a certain level of obligation on the country to contribute to continental and global efforts in this arena. Here, again, the Department of Environmental Affairs and Tourism is the department charged with primary responsibility for South Africa's implementation efforts in this arena and should co-ordinate and lead the development of national policy in this field. Once again, the Water Research Commission can play a leadership role within the water sector and support research that will assist the national policy development processes. The insights and experiences gained within the water sector represent an important contribution to our collective knowledge of the processes involved. Ultimately, a multi-sectoral policy response will be needed to resolve this issue and it will be essential for all sectors to converge and co-ordinate their efforts. The process level research that has been conducted to date could provide useful information for global- and continental-scale modelling studies.

A.1.7 Issue 7: Implications of MDGs for water resources

The research question for issue 7 is:

What are the implications of meeting the Millennium Development Goals (MDGs) for water services and sanitation on environmental functioning within the hydrological cycle, and hence for water resources management?

There is a high coverage in terms of the tertiary catchments where research projects that are pertinent to this issue have been undertaken. The primary catchments with high coverage include the Orange, Vaal, Limpopo and Olifants, as well as the coastal regions of South Africa (**Figure A13**).

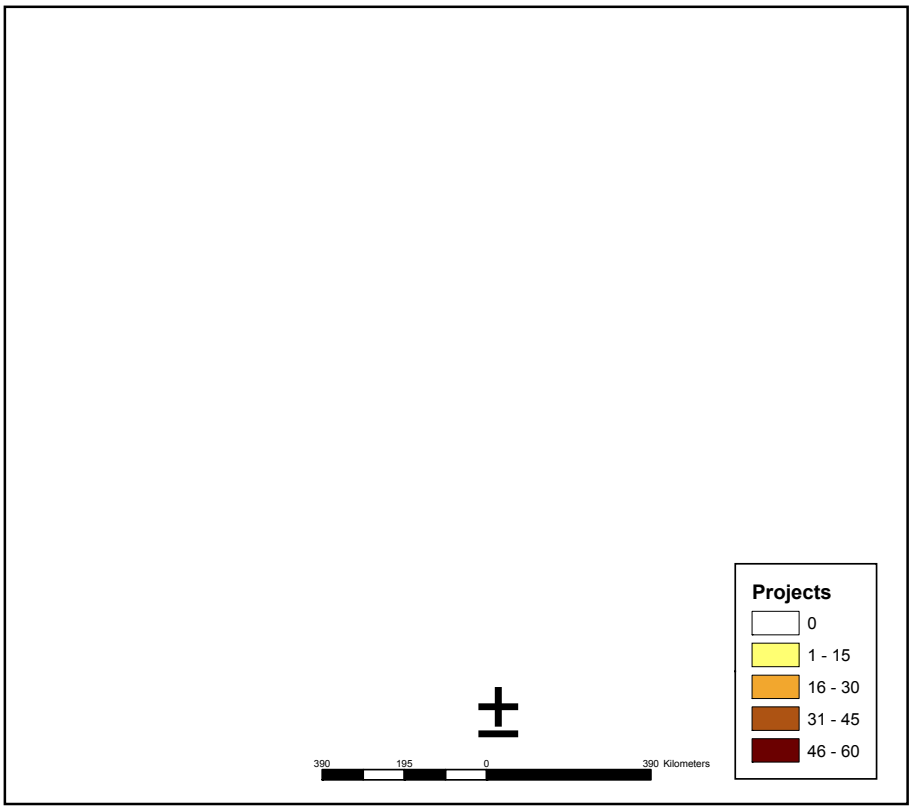


Figure A13: Tertiary catchment distribution of WRC research records relevant to issue 7 (n=95).

The millennium development goal: to ensure environmental sustainability, is fully applicable to the provision of potable water services and improved sanitation systems. This goal aims to reduce by half, the proportion of people who lack sustainable access to safe and reliable supplies of drinking water. Many of the studies that have been undertaken are relevant as background information to this issue, and the information they contain would require minimum analysis or integration to derive new insights related to the MDGs. The majority of the research was undertaken at a national scale, with process research dominating, but some policy related research has also been undertaken (**Figure A14**). Catchment and site-specific research projects are dominated by situation assessment and process orientated research, respectively.

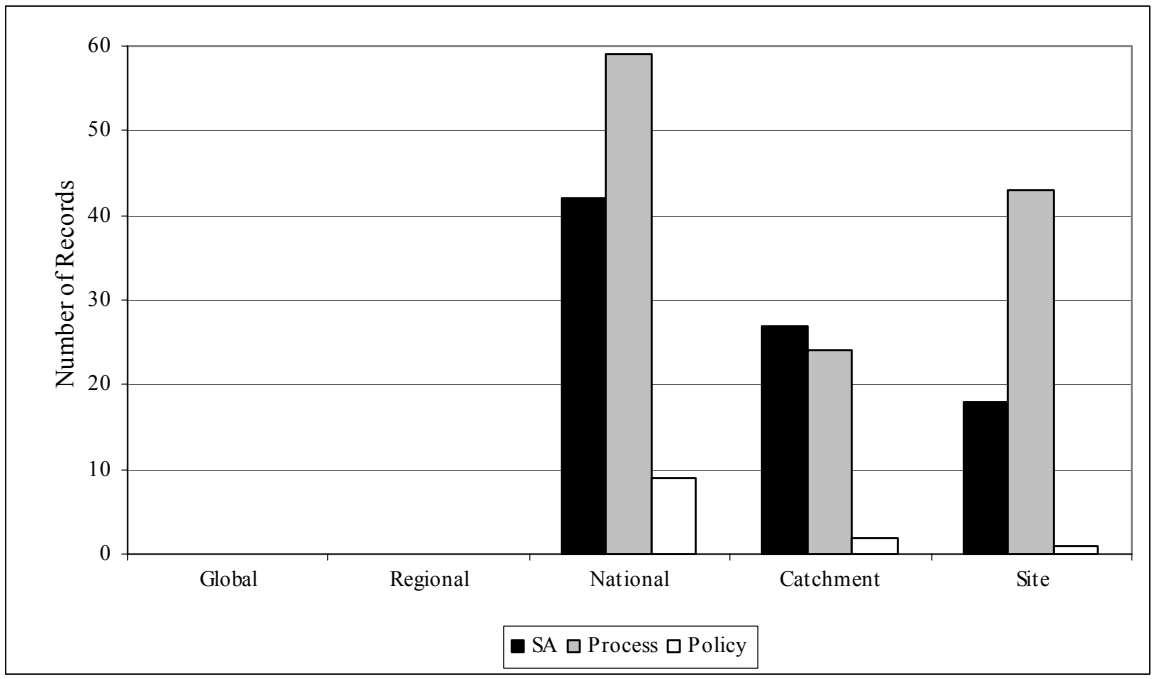


Figure A14: Number of WRC research records per level and scale of study relevant to issue 7 (n=207).

In broad terms, practically every research project funded by the Water Research Commission could contribute to this issue in several ways. An important, central issue: how to determine and then maintain a balance between resource utilization (to provide goods and services to society) and resource protection (to ensure that the water resources remain capable of providing these goods and services), forms the backbone of all water resource management goals.

A.1.8 Issue 8: Atmospheric emissions and their impact on water resources

The research questions for issue 8 are:

What are the scope and significance of the impacts of current and projected patterns of atmospheric emissions (loads, concentrations, spatial distribution, forms {NOx, SOx, particulates, organics, carbon compounds}) from land-based activities for the hydrological cycle and hence for water resources management? What are the environmental processes governing the fate and transport of these substances within the hydrological cycle? What are the options for policy responses from the water sector or in collaboration with other sectors?

Those tertiary catchments where relevant research to this issue has been undertaken are found primarily along the Vaal River (**Figure A15**). No more than three studies have been conducted in these catchments.

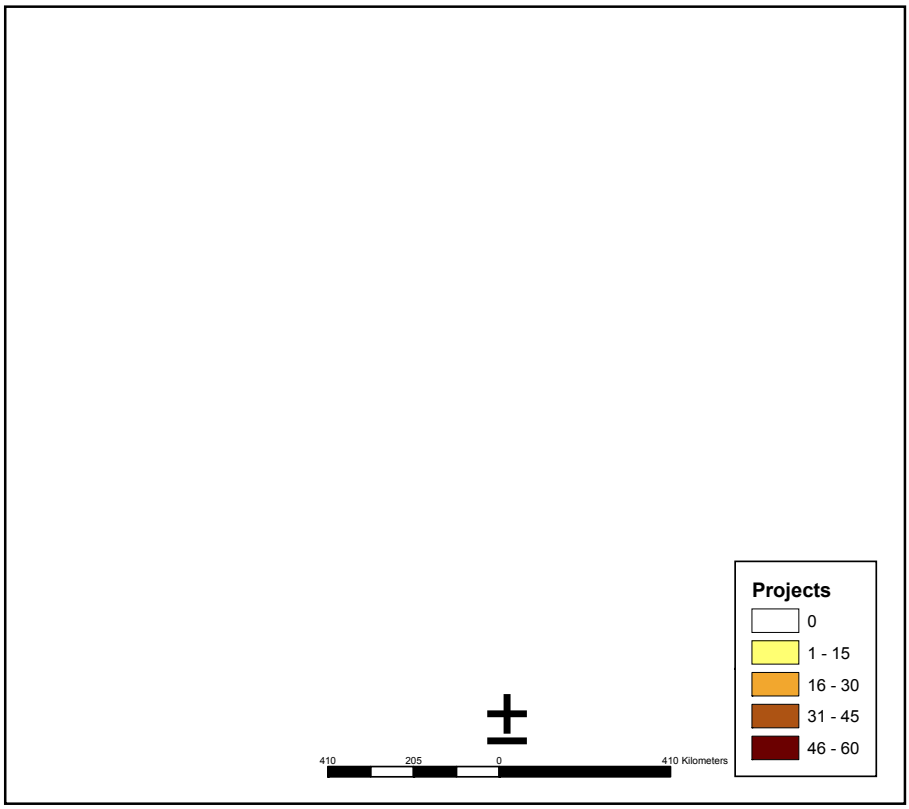


Figure A15: Tertiary catchment distribution of WRC research records relevant to issue 8 (n=3).

A total of five studies have been undertaken, three of which were conducted at a catchment scale (**Figure A16**). Research on the relationships between atmospheric deposition and water and soil quality, and pollution management, were most relevant to this issue.

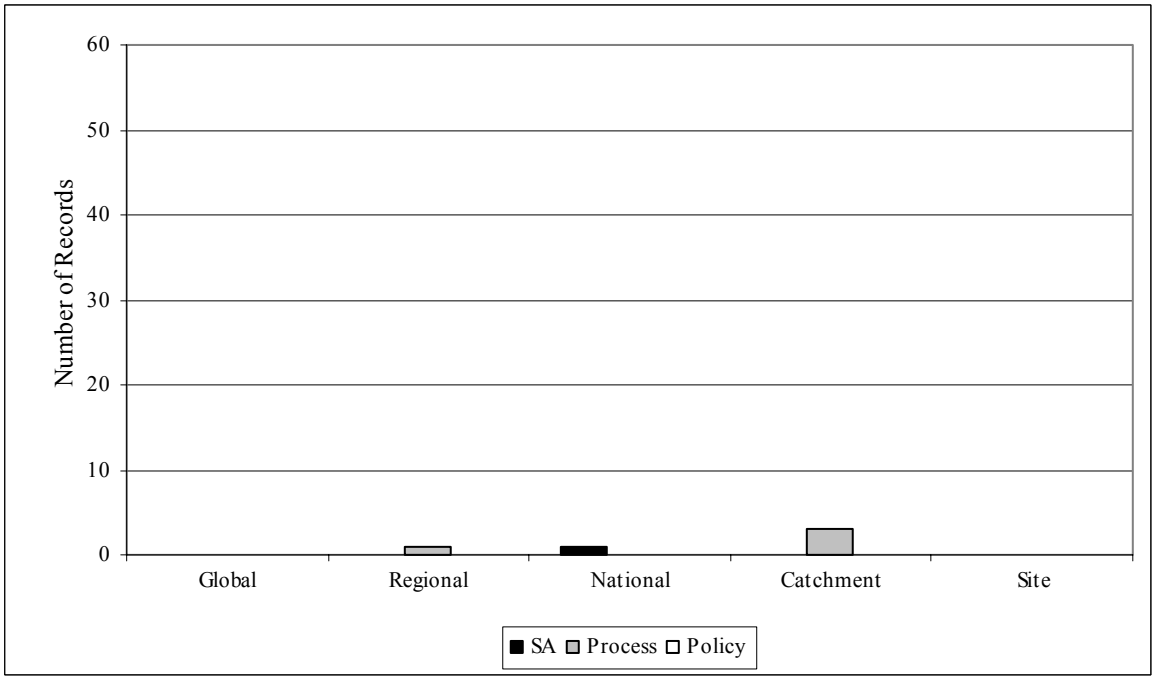


Figure A16: Number of WRC research records per level and scale of study relevant to issue 8 (n=5).

There has been (and will continue to be) considerable dissent amongst researchers, industrialists and water resource managers around the scale, extent and severity of possible consequences of atmospheric emissions on South Africa's water resources. Typically, these differences of opinion centre on the "size" and "characteristics" of the emissions, where (and how) these could potentially influence terrestrial and aquatic ecosystems, and their likely consequences for human populations. The result has been that there is no significant advance in national policy responses to manage and mitigate the potential consequences.

This polarized debate is not new and cannot be resolved in a simplistic way by merely repeating studies that have been carried out in the past in an effort to "improve the numbers". Instead, there is an acute need to design an appropriate collaborative study that engages all stakeholders, and which extends over an appropriate scale, which will provide unequivocal evidence as to the quantitative extent and forms of atmospheric emissions, their spatial distribution across the southern African landscape, the forms in which materials are deposited on specific landscape units, and their subsequent fate. Closely-related issues such as the impacts of specific atmospheric emission components and compounds on soil structure and chemistry, vegetation physiology, crop productivity, and food and water security need to be addressed with a multidisciplinary and multi-organizational approach. The Water Research Commission could play a leading role in convening and guiding this research team, and ensuring that all uncertainties are properly addressed.

A.1.9 Issue 9: Migration and urbanization impacts on water in the environment

The research questions for issue 9 are:

What are the current and projected patterns of migration and urbanization? What are the potential impacts on water in the environment, either directly as a result of land use changes or effluent discharges, or indirectly through changes in water demand patterns?

Those tertiary catchments where research relevant to the issue has been undertaken includes those along the south-eastern coast of South Africa, and some of those within the Orange, Vaal and Limpopo primary catchments (**Figure A17**).

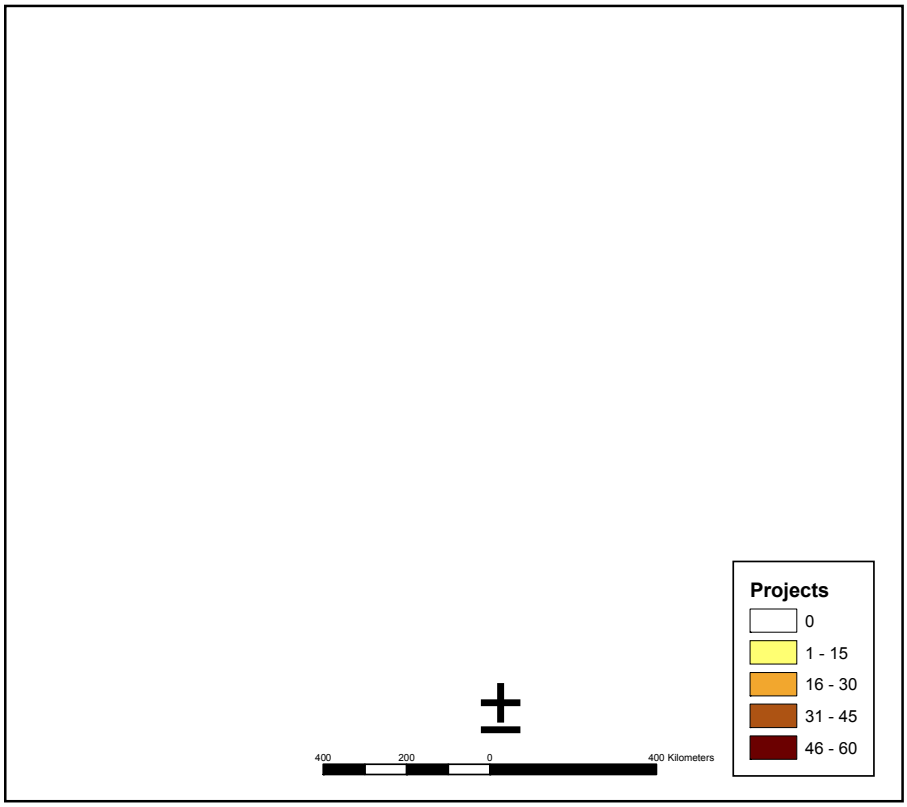


Figure A17: Tertiary catchment distribution of WRC research records relevant to issue 9 (n=40).

The focus of research relevant to this issue includes runoff from formal and informal urban, rural and peri-urban settlements and its effect on the water quality of receiving aquatic systems (rivers, reservoirs and wetlands). Another, related research focus area has concentrated on improving the supply of water to formal settlements, including the exploration and subsequent development of groundwater resources, with a particular emphasis on rural communities. Additional studies have targeted water quality issues such as sedimentation in estuaries due to landuse changes, and the incidence (and treatment/removal) of specific pathogens and diseases in potable water, which were originally caused by or attributed to improper waste disposal practices. The majority of this research was conducted at a national scale and was primarily process orientated (**Figure A18**).

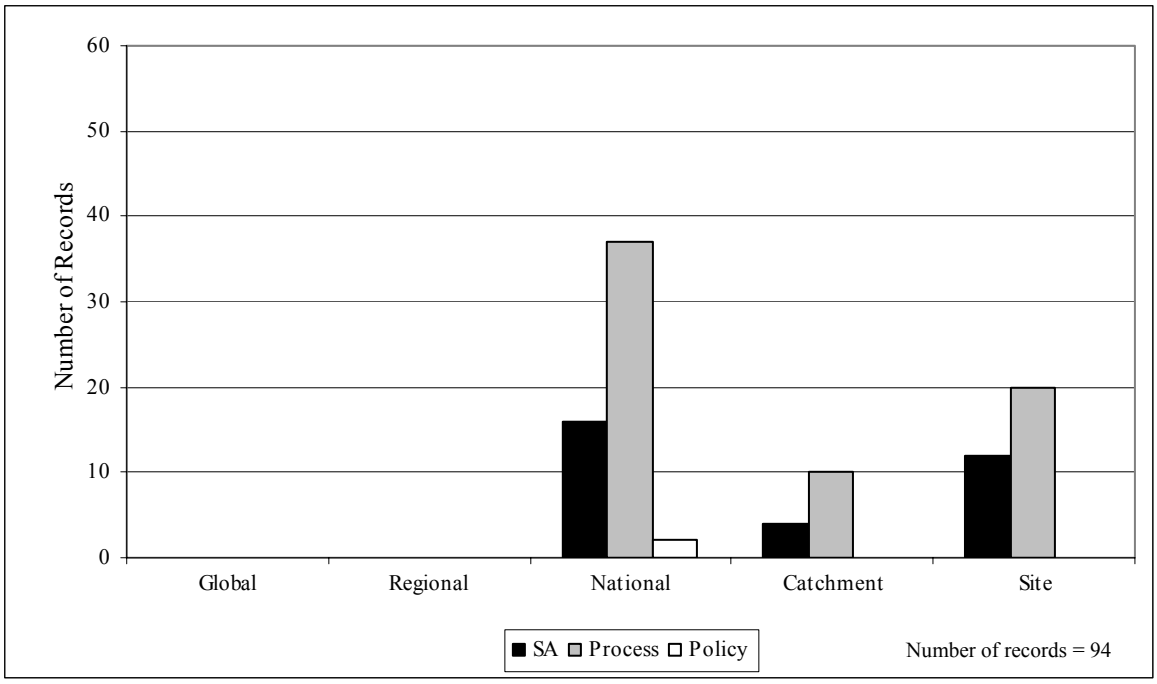


Figure A18: Number of WRC research records per level and scale of study relevant to issue 9 (n=94).

The prevailing and projected patterns of population migration and urbanization are not fully understood and this hampers proper planning for the provision of a variety of services to formal and informal communities. These services include the provision of land, housing, potable water, sanitation, waste disposal and electricity supplies. The interacting influences of social, demographic, cultural, and economic drivers, together with the political imperatives to redress past inequities, have direct and indirect effects on the poverty levels of individuals and communities, and also influence personal preferences or options for specific geographic regions, or types and levels of economic activity. Clearly, the scope of this issue is far wider than the water sector alone, though the water sector has a pivotal role to play in assisting national efforts; in particular, the water sector can provide good guidance at policy level to prevent injudicious decisions that could adversely affect the country's water resources.

The Water Research Commission and other research funding agencies have supported several research projects that have focussed on understanding the causes and nature of runoff patterns from urban settlements, and the development of appropriate water treatment technologies to minimize the adverse impacts of poor quality runoff on aquatic ecosystems. Whilst this information is extremely important for proper management of urban settlements, our ability to predict the spatial and temporal patterns of migration and urbanization is still poor.

A.1.10 Issue 10: Persistent organic pollutants

The research questions for issue 10 are:

What are the scope and significance of past, current and projected patterns of use of persistent organic pollutants (POPs) in the environment? What are the environmental processes governing the fate and transport of POPs within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?

Very little research related to this issue has been undertaken; the research that has been conducted primarily took place within the Orange and Vaal catchments (**Figure A19**).

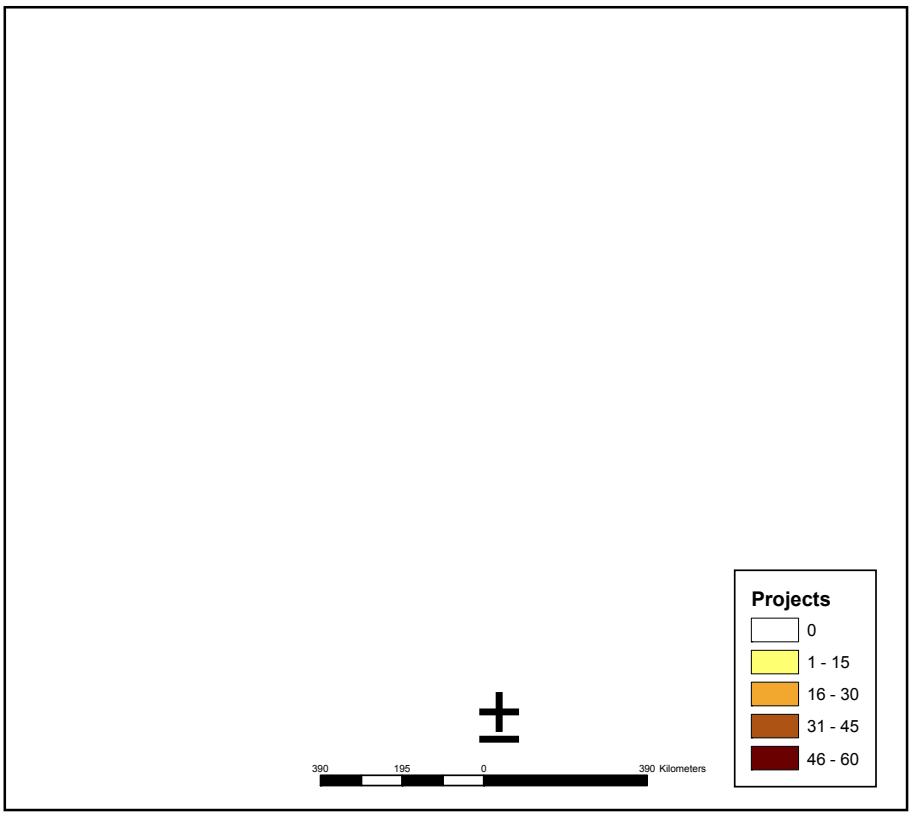


Figure A19: Tertiary catchment distribution of WRC research records relevant to issue 10 (n=10).

The majority of research was undertaken at a national scale (**Figure A20**) and focused on pesticide occurrence in surface and groundwater resources, water treatment options to reduce pesticide concentrations before use, and the effects of pesticides on riverine ecosystems. One research project has been commissioned to survey the presence and levels of certain persistent organic pollutants in the major waters in South Africa.

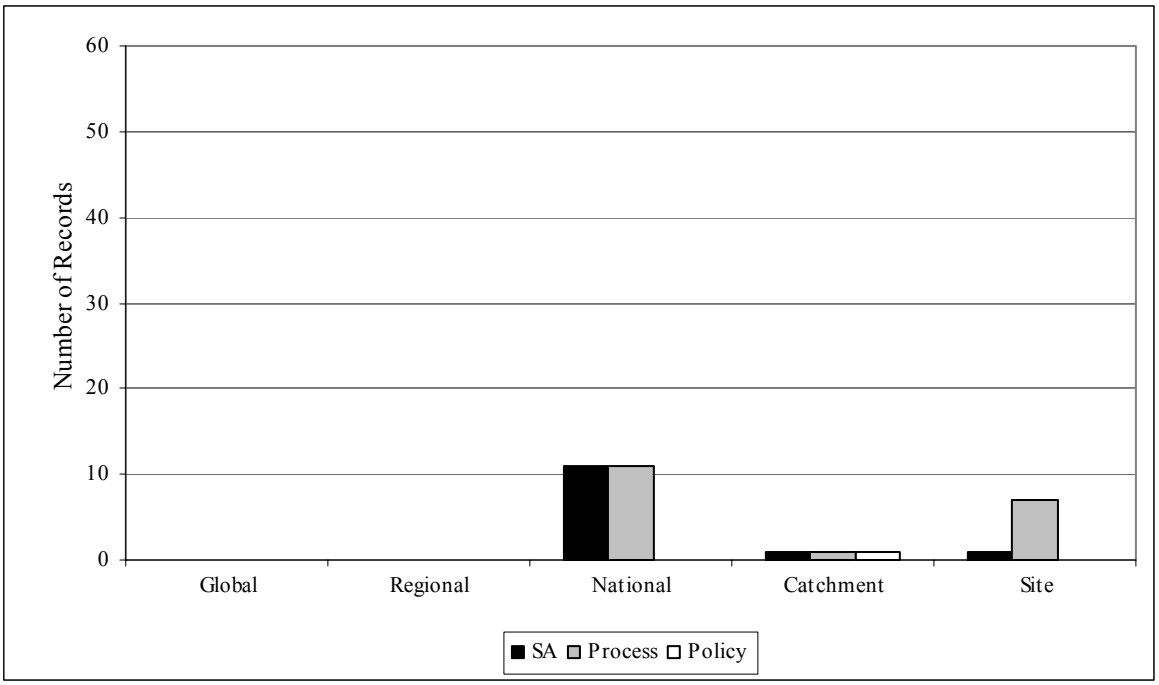


Figure A20: Number of WRC research records per level and scale of study relevant to issue 10 (n=32).

To date, relatively few research projects have been carried out on persistent organic pollutants though the topic is gaining prominence due to the United Nations Treaty on the control of these substances. A particular problem area has been the high cost of conducting chemical analyses for organic compounds, which has hindered the implementation of routine monitoring programmes for these substances. This difficulty is compounded by the need to develop new analytical techniques to detect progressively greater numbers of new organic compounds that appear each year. These compounds include a wide variety of substances derived from the country's expanding chemical industry, as well as increased numbers of novel pharmaceutical products, including endocrine disrupting substances.

There is a pressing need for a national-scale survey and inventory of the current situation regarding the variety of organic compounds present in the different components of the hydrological cycle, so that attention can be directed to those areas where the greatest problems occur. In support of this effort, greater attention also needs to be paid to the fate and transport of these substances in the freshwater components of the aquatic environment, and their implications for ecosystem and human health.

A.1.11 Issue 11: Radioactivity

The research questions for issue 11 are:

What is the current and projected status of both natural and human-induced radioactivity in the components of the hydrological cycle? What are the environmental processes governing the fate and transport of radioactivity within the hydrological cycle? What are the potential impacts on water resources, in terms of use and protection? What are the possible policy and regulatory responses?

Very little research has been undertaken to answer the questions raised in issue 11. A total of seven studies have been conducted that are relevant to this issue and these have been carried out in the mining areas of the Rand and in the Pofadder area of the Northern Cape Province (**Figure A21**).

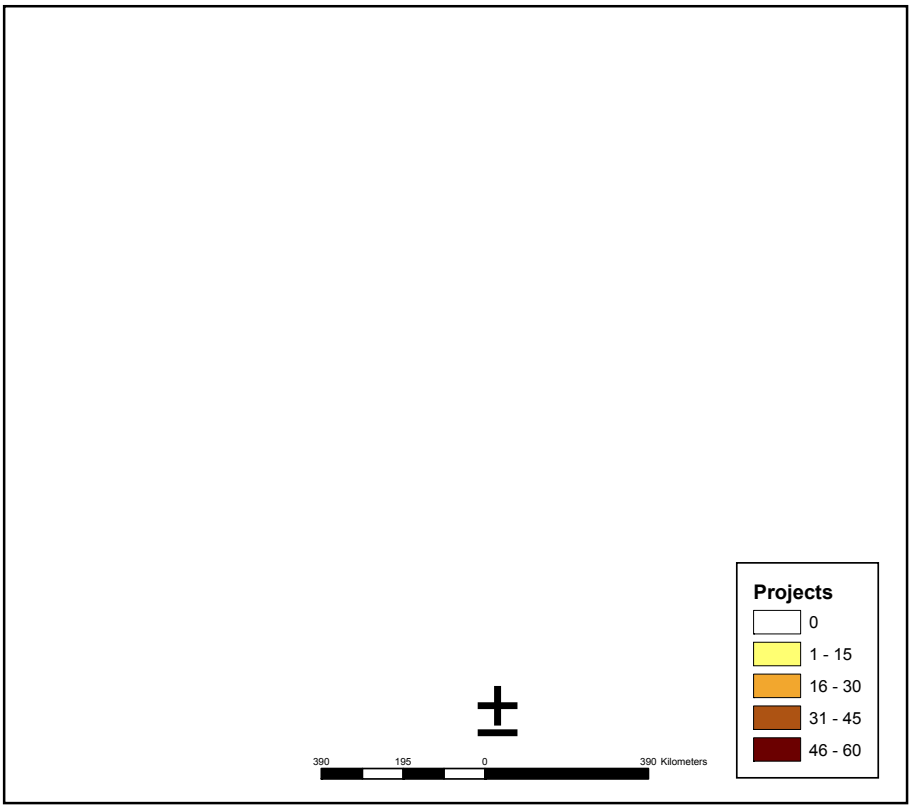


Figure A21: Tertiary catchment distribution of WRC research records relevant to issue 11 (n=3).

The research conducted to date has focussed on predicting the spatial distribution of naturally occurring radioactivity in groundwater within South Africa, the water requirements of mines where uranium is present, the implications of uranium in effluents from mines, and risk assessments of radionuclides in sediments. The majority of this research has been conducted at a national scale and at the level of situation assessment (**Figure A22**).

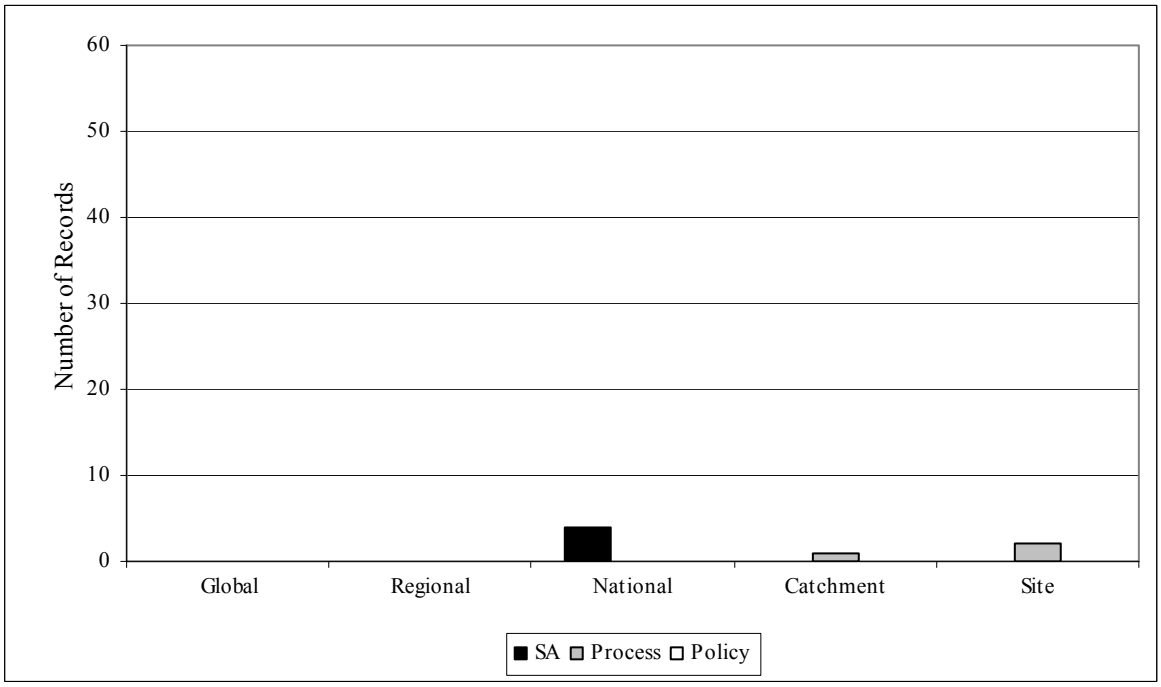


Figure A22: Number of WRC research records per level and scale of study relevant to issue 11 (n=7).

There is a need to conduct a broad-scale situation assessment of the extent and types of radioactivity present in the different components of the hydrological cycle in South Africa, and to determine the extent to which any radioactivity may be due to natural geological sources, or due to human activities, particularly the disposal of mining wastes. This will provide clear directions for the development of national policy, and will also allow the necessity for appropriate remedial measures to be evaluated and implemented.

A.1.12 Issue 12: Persistent inorganic pollutants

The research questions for issue 12 are:

What are the scope and significance of past, current and projected patterns of use of persistent toxic inorganic pollutants in the environment? What are the environmental processes governing the fate and transport of persistent inorganic pollutants (PIPs) within the hydrological cycle? What are the implications of these patterns on components of the hydrological cycle? What are the possible policy and regulatory responses?

The tertiary catchments where research projects relevant to this issue have been undertaken are located within the Vaal and Olifants primary catchments (**Figure A23**).

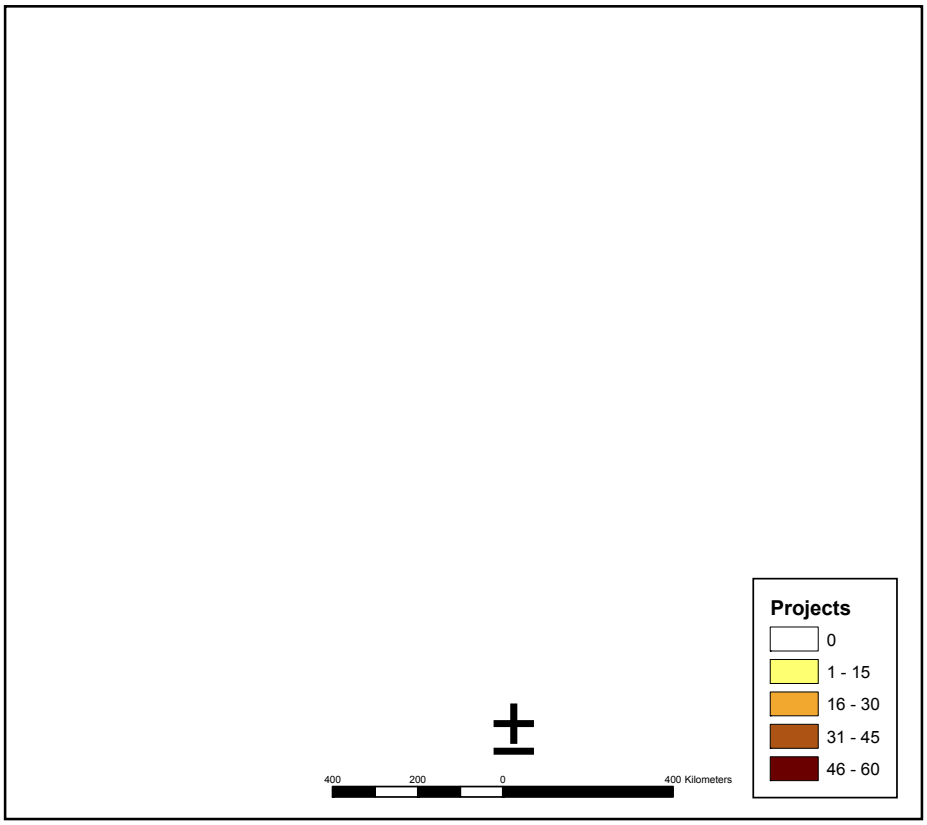


Figure A23: Tertiary catchment distribution of WRC research records relevant to issue 12 (n=9).

The majority of the research has been undertaken at a national scale (**Figure A24**), where research has focused primarily on toxic effluents and heavy metals in wastewater, and their effects on fish, soil, groundwater, riverine ecosystems and the health of rural communities.

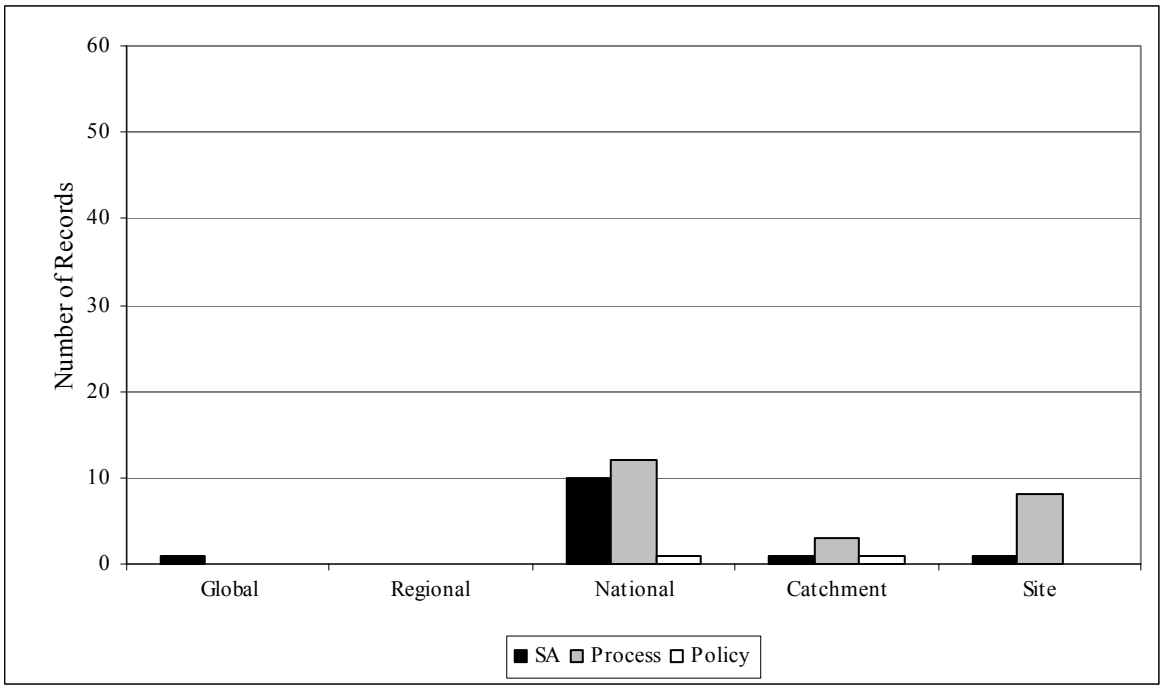


Figure A24: Number of WRC research records per level and scale of study relevant to issue 12 (n=37).

Persistent inorganic pollutants consist principally of metal and semi-metal ions that exert a variety of toxic effects on aquatic and terrestrial organisms. These substances exist in many different forms and are derived from both natural geological causes and man-made activities. Several research funding organizations, including the Water Research Commission, have supported a number of research projects on these substances. Most projects have focussed on efforts to determine the extent and biological availability of these substances in freshwater aquatic ecosystems and estuaries, and evaluate their effects on specific groups of aquatic organisms. Whilst these studies have revealed the widespread presence of these toxic inorganic substances in many aquatic ecosystems, there is less understanding of the precise role and significance of these substances in such ecosystems. Similarly, several studies have provided clear evidence that the majority of these substances have been derived from human activities, especially the disposal of mining and industrial wastes, and this information, together with specific toxicological studies, has formed the basis for the derivation of water quality guidelines for specific toxic inorganic substances. A smaller quota of research work has focussed on the fate and transport of these substances in aquatic ecosystems. As a result, our knowledge of the extent to which these substances may be bound within sediments and re-mobilized under specific sets of circumstances, as well as their precise implications for ecosystem structure and functioning, is incomplete and insufficient to formulate clear rehabilitation policies and methodologies.

The Water Research Commission is ideally placed to play a leading role in resolving these problems through the development of a national strategy to determine the extent, significance and potential for rehabilitation of the different toxic inorganic substances that are present in aquatic ecosystems. Ideally, targeted research should include clear assessments of the ways in which aquatic ecosystems act as temporary and permanent sinks for these substances. Since South Africa shares many of its river systems with neighbouring countries, these substances also pose potential problems for our neighbours. This situation needs to be clarified, and then supported by the development and implementation of appropriate policy instruments and management strategies.

A2. Programme 2: Biodiversity

Programme 2 comprises 4 issues, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

Programme 2 issues:
- Secondary effects of climate change on aquatic ecosystems;
- Biodiversity and Inter-Basin Transfers (IBTs);
- Upstream impacts and ecological roles of flow regulating structures; and
- Biodiversity and WRM indicators.

A.2.1 Issue 13: Secondary effects of climate change on aquatic ecosystems

The research questions for issue 13 are:

What secondary and/or tertiary effects (cumulative effects) is climate change (temperature, hydrology) likely to have on the structure, function and composition of ecosystems related to the components of the hydrological cycle? What are the implications for the quality, reliability and availability of water and associated goods and services derived from water resources? What are the options for policy responses?

The majority of studies that are relevant to this issue were conducted in the Vaal, Olifants and Thukela primary catchments and along the southern coast of South Africa (**Figure A25**).

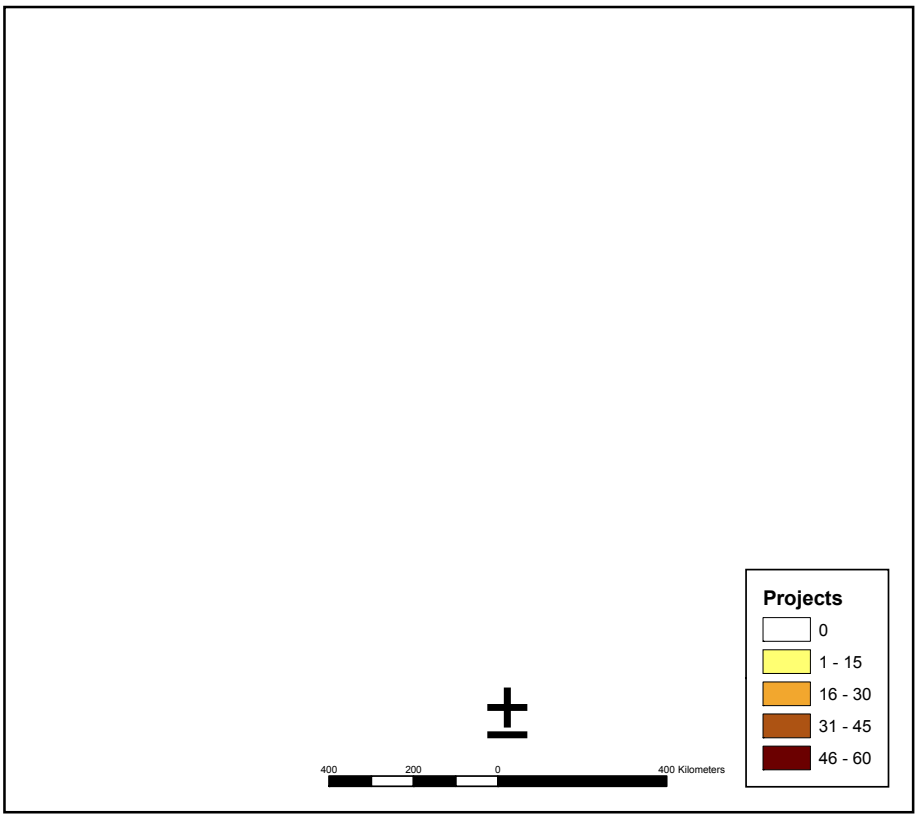


Figure A25: Tertiary catchment distribution of WRC research records relevant to issue 13 (n=29).

Although no research has been conducted that can provide direct or specific answers to the questions posed in issue 13, the Water Research Commission has funded a total of 64 studies that could provide useful background information pertinent to this issue. Research has been undertaken at all scales of study except global, with national and catchment scale studies being the most predominant (**Figure A26**). The majority of research has been process orientated, while at the national scale situation assessment studies have also been common. The focus of research has been primarily on understanding ecosystem processes and their tolerance to change, water use and quality, water resource management and modelling climate variability.

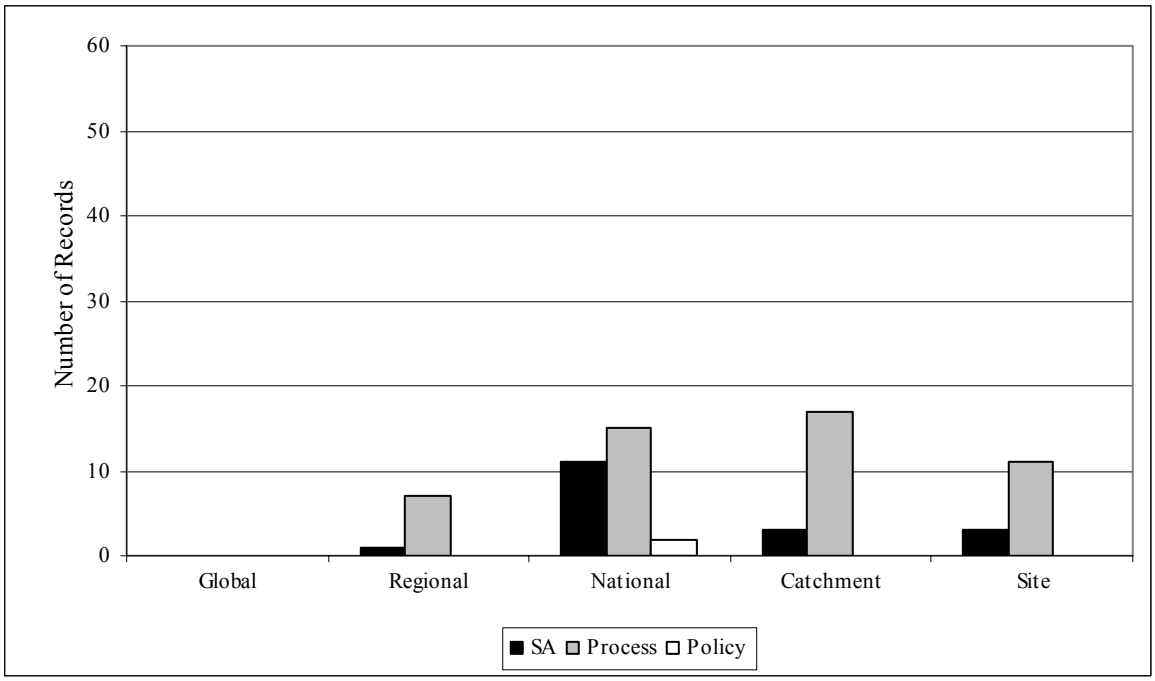


Figure A26: Number of WRC research records per level and scale of study relevant to issue 13 (n=64).

None of the research projects funded by the Water Research Commission have focussed directly on the questions related to this issue. However, the information derived from several research projects has provided indirect information has helped to extend and consolidate our knowledge and understanding of the potential indirect effects of climate change on several hydrological processes. This research arena has been identified as a high priority by the Water Research Commission and new research projects directed at deriving answers to some of the specific questions posed above will be based on the consolidated knowledge and understanding derived from earlier projects. Particular emphasis will be placed on gaining new knowledge of indirect and cumulative effects that are transmitted and transformed along the longitudinal axes of aquatic ecosystems.

A.2.2 Issue 14: Biodiversity and IBTs

The research questions for issue 14 are:

What are the impacts of existing and proposed inter-basin transfer schemes on the structural, functional and compositional aspects of biodiversity at all scales (genetic to landscape)? What are the options for policy and regulatory responses?

Those tertiary catchments where research has been undertaken that is relevant to issue 14 are found within the primary catchments of the Orange, uMngeni, Phongolo, Olifants and Crocodile rivers (**Figure A27**).

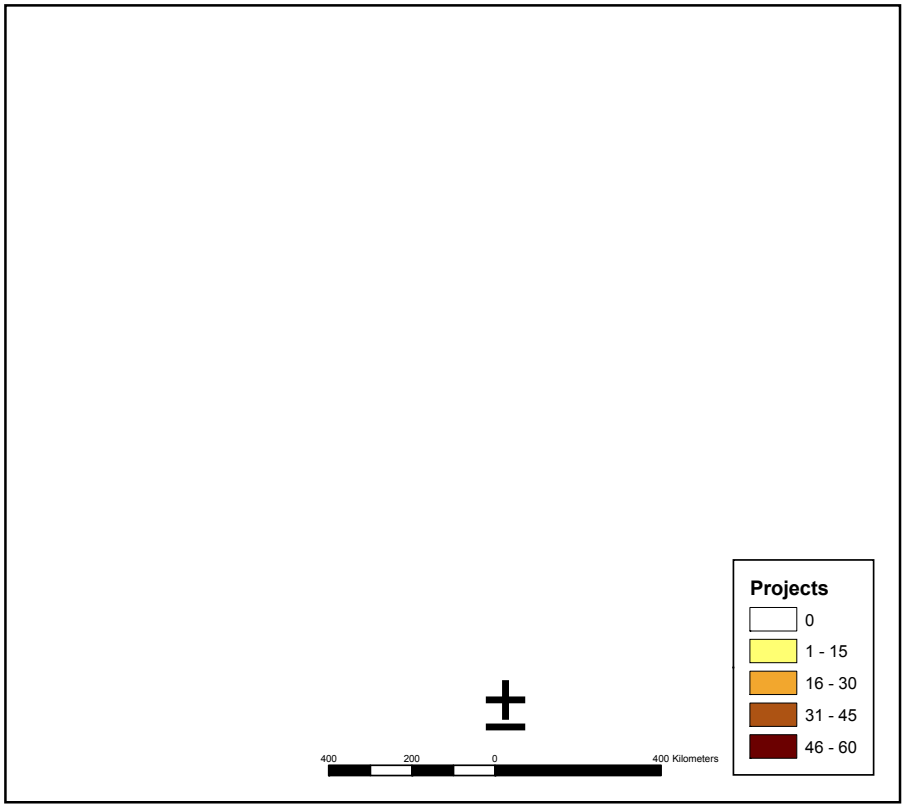


Figure A27: Tertiary catchment distribution of WRC research records relevant to issue 14 (n=6).

Very little quantitative research has been conducted in this field; only 13 studies can provide some insights into the research questions posed for this issue. Some research has been conducted at all scales except regional, whilst no research funded by the Water Research Commission has been undertaken at the policy level (**Figure A28**). The primary focus of research that has been undertaken has been on the downstream impacts of dams and water supply reservoirs, the operational management of IBTs and their effects of aquatic ecosystems, and on understanding the characteristic ecological functions of rivers in general.

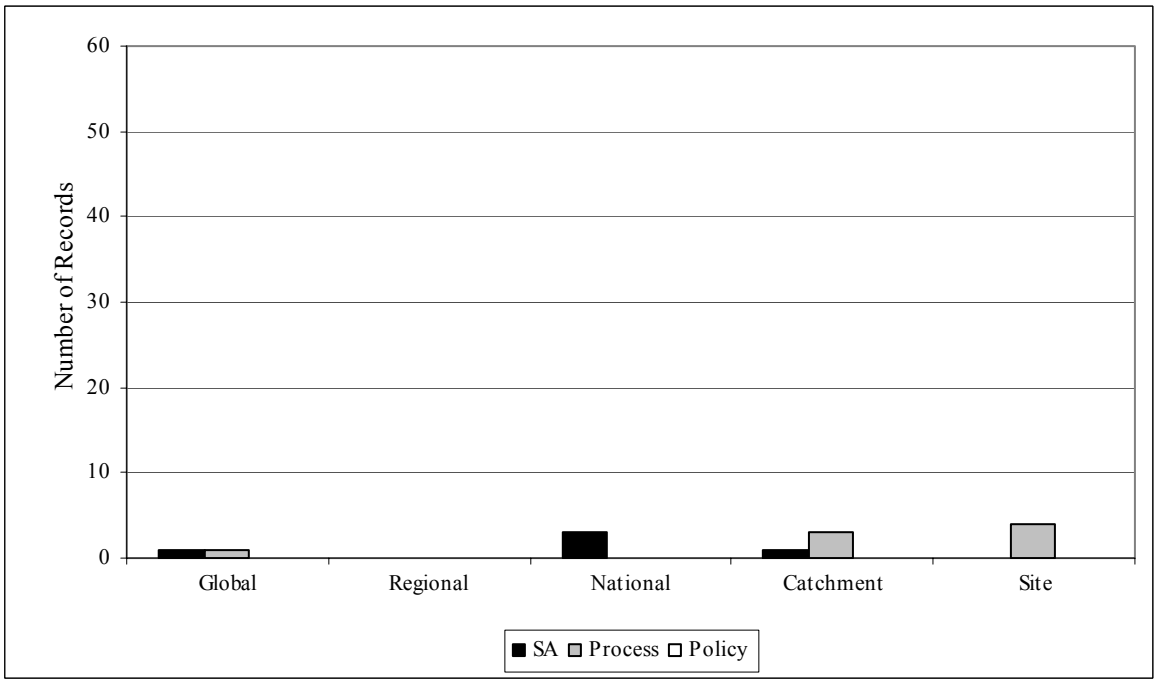


Figure A28: Number of WRC research records per level and scale of study relevant to issue 14 (n=12).

A large proportion of the research that is relevant to this issue consists of review studies, where the information obtained for South African systems has been compared to similar studies conducted in Australia and North America. A major emphasis within South African research projects has been driven by concerns about the potentially dramatic alterations in riverine populations of aquatic organisms and the resulting adverse impacts on ecosystem functioning that are associated with both the donor and recipient systems linked by inter-basin water transfers. Whilst this work has provided useful insights into both general and specific ecosystem processes, there are still large gaps in our understanding of the effects of inter-basin water transfers on the structural, compositional and functional aspects of biodiversity. Similarly, our understanding of the comparative advantages and disadvantages linked to different structural configurations of inter-basin water transfer schemes is inadequate, though there is some understanding of specific engineering processes that could be deployed to minimize the transfer of biological material between donor and recipient systems.

Given the progressively increasing demands for water, several South African river basins are approaching closure where there is little available water that can be allocated to meet demands for water. A similar situation exists in several of our neighbouring countries. This will inevitably lead to an increase in the transfer of water from "water-rich" catchments to "water-poor" catchments, thereby increasing the likelihood that significant biological changes could occur at scales from genetic modification to population transformation. The situation could be compounded in future if the postulated long-distance transfers of water from rivers as far north as the Zambezi and Zaire systems are realized. At present, our knowledge levels are insufficient to allow the provision of unequivocal inputs to the formulation of appropriate policy responses. Therefore, a comprehensive situation analysis is required of the state of inter-basin water transfers throughout the entire southern African region, as well as focussed research projects to determine the specific effects of inter-basin water transfers on biodiversity. This will then form a firm foundation for the development of appropriate policy.

A.2.3 Issue 15: Upstream impacts and ecological roles of flow regulating structures

The research questions for issue 15 are:

What are the upstream impacts of flow-regulating structures, including dams, reservoirs and weirs? What are the potential ecological roles within the hydrological cycle of flow-regulating structures in surface water bodies? What are the implications for water resources management?

Most of the research projects that are pertinent to this issue were undertaken in those tertiary catchments along the Orange River, within the Olifants and Limpopo catchments and along the coastal belt of South Africa (**Figure A29**).

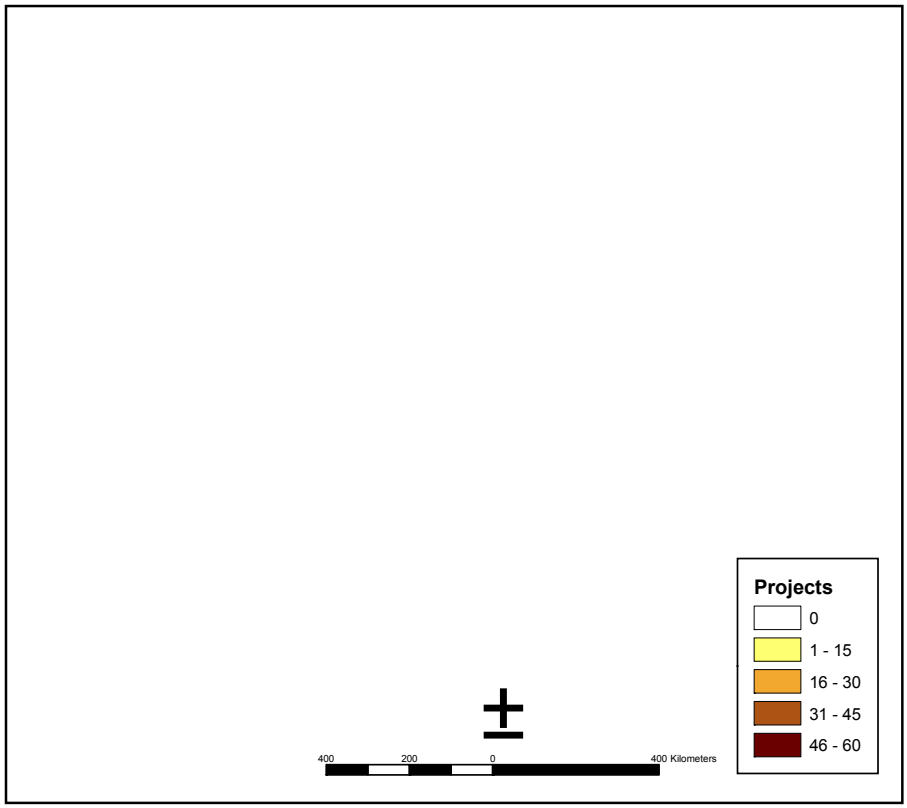


Figure A29: Tertiary catchment distribution of WRC research records relevant to issue 15 (n=6).

Little research has been conducted specifically on the upstream impacts of flow regulating structures although the learning from studies on dams, reservoirs and weirs can provide some relevant background information. Most of the relevant research that has been undertaken has focussed on the population dynamics of blackfly and algal blooms and their biological control, sediment transport and yield in rivers, reservoir sedimentation, pre-impoundment studies and impacts on river morphology. The majority of the research was conducted at a national and catchment scale. Very little policy related research was undertaken, with the majority of research being situation assessment and process oriented (**Figure A30**).

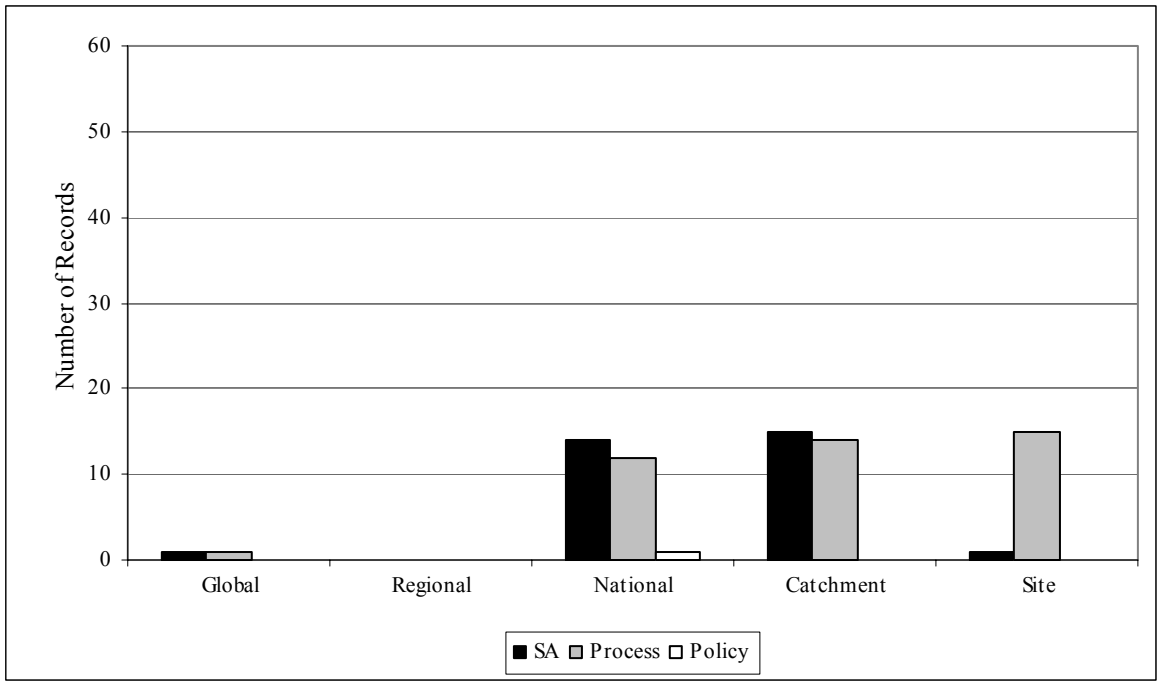


Figure A30: Number of WRC research records per level and scale of study relevant to issue 15 (n=67).

Inevitably, the construction and operation of a dam or any other flow-regulation structure in a river, exerts a series of positive and negative effects on both upstream and downstream sections of the river. The transformation of a previously riverine environment into a lacustrine environment upstream of a flow control structure, results in a wide array of physical, chemical and biological changes. This transforms the structure, composition and functional attributes of biological populations, and sets in place a series of larger, landscape-scale changes that affect the ecological integrity of the entire river system. Little attention has been paid to the now "restricted" populations of organisms that are confined to the river reaches upstream of the flow regulation structure.

Whilst the original objective underlying the decision to construct the flow-regulation structure may have centred on the provision of assured water supplies for off-channel use, the resultant ecological changes have often been overlooked, or ignored, or considered to be of lesser importance. Inevitably, the potential social and economic benefits are considered to be of greater value than the likely ecological costs. Mitigation efforts have centred on the derivation of appropriate reservoir operating rules in attempts to provide sufficient water to sustain downstream riverine ecosystems. These have also been supplemented by catchment management actions designed to minimize sediment accumulation within the reservoir, and provide a high assurance of water yields that may be abstracted from the reservoir. From a conservation perspective, the presence of a new "artificial" ecosystem (the reservoir) poses important philosophical questions around the validity and desirability of attempts to protect the original riverine organisms that are now restricted to a new lacustrine environment.

A.2.4 Issue 16: Biodiversity and WRM indicators

The research questions for issue 16 are:

How does the current and emerging suite of WRM indicators reflect the dimensions (structure, composition and function) and scales (genetic to landscape) of biodiversity? What would be the characteristics of appropriate indicators for WRM that properly reflect all the dimensions and scales of biodiversity?

The areas that have received the most attention in terms of this issue are located within the Crocodile catchment in general, and along the Sabie River in the Kruger National Park in particular (**Figure A31**). Secondary areas where research has been undertaken include those tertiary catchments along the coast and within the Olifants, Limpopo and Orange catchments.

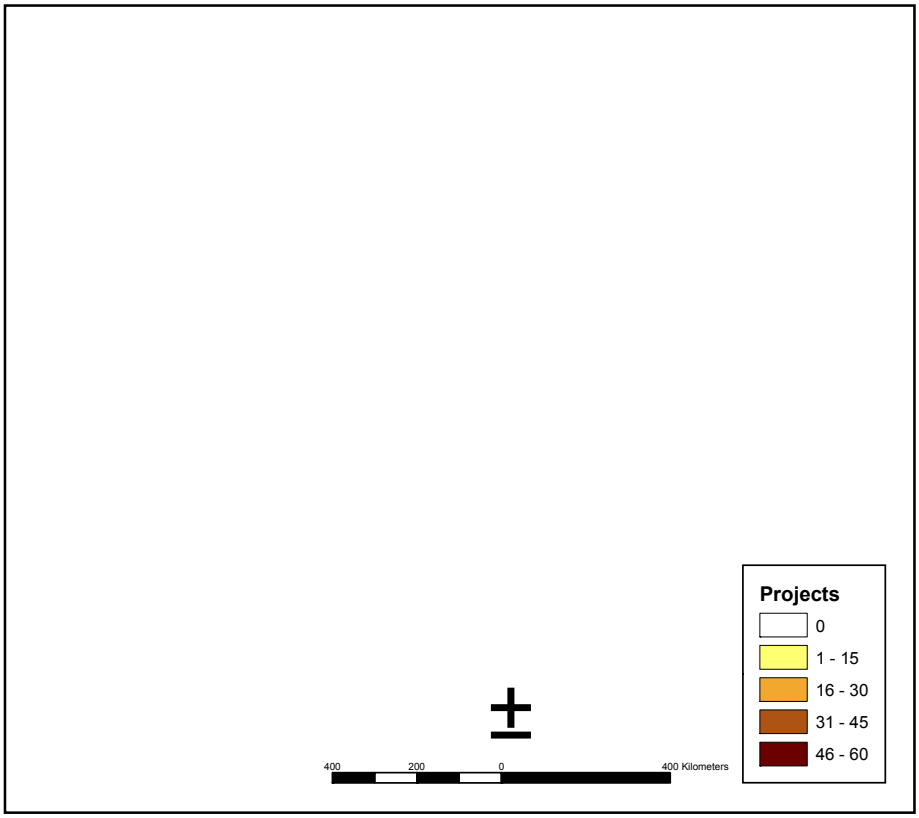


Figure A31: Tertiary catchment distribution of WRC research records relevant to issue 16 (n=31).

Those areas of research funded by the Water Research Commission that are pertinent to this issue include assessments of the effects of streamflow reduction activities, the development of a geomorphological classification of river reach types, improved understanding of riparian ecosystems, and indicators of estuarine water quality. The majority of research has been conducted at the national and catchment scales (**Figure A32**). At a national scale, situation assessment and process research dominate, with some research focusing on policy related research. At the catchment scale, process level research is most common.

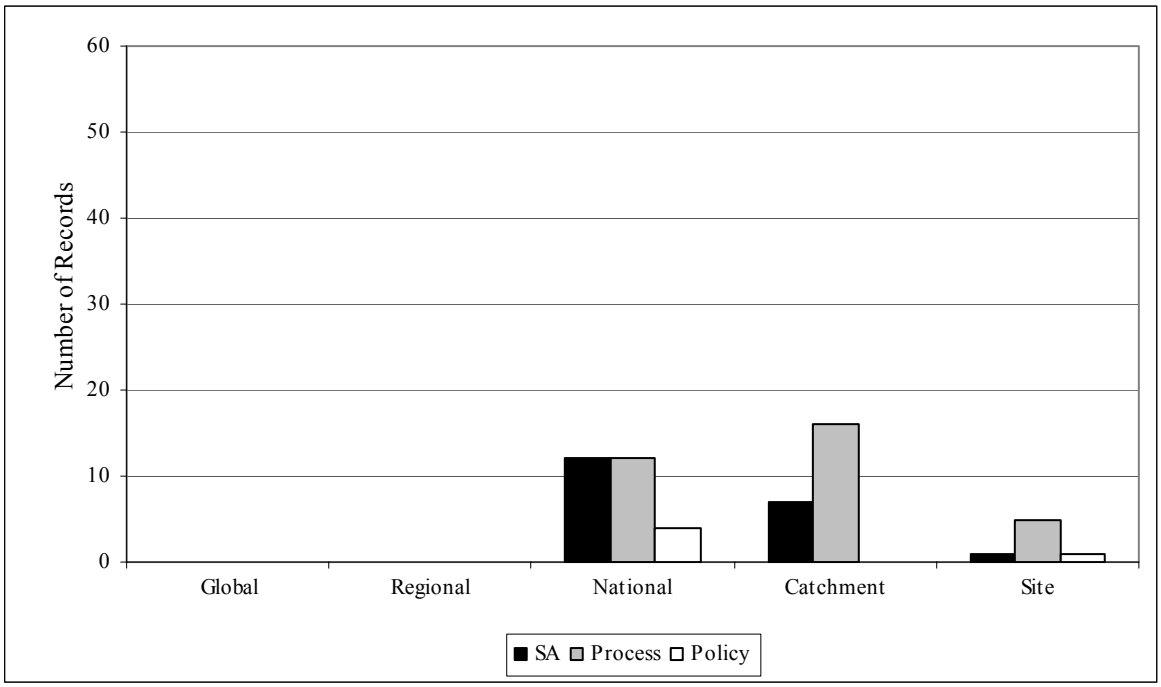


Figure A32: Number of WRC research records per level and scale of study relevant to issue 16 (n=51).

At present, South Africa possesses very few water resource management (WRM) indicators that provide insights into the structural, compositional and functional aspects of biodiversity. Instead, most WRM indicators merely reflect the availability and (seasonal and inter-annual) variability of water flows, the variety of different aquatic organisms present in a river system and the presence or absence of key indicator species, the state and condition of the riparian zone, and the presence (or absence) of water quality problems as indicated by alterations to chemical features of a river system. Clearly, this situation is inadequate for a reliable assessment of the different scales and dimensions of biodiversity, and also hampers sensible decision-making.

The Water Research Commission has recognized this arena as a high priority and has already commissioned a detailed position paper on this topic. The position paper will identify the current "state of the art", examine possible shortcomings in current approaches, and propose appropriate new research that will address these inadequacies.

A3. Programme 3: Impact and management of introduced species

Programme 3 comprises 2 issues, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

Programme 3 issues:
- Implications of Genetically Modified Organisms (GMOs); and
- Nuisance species.

A.3.1 Issue 17: Implications of GMOs

The research question for issue 17 is:

What are the potential impacts on water resources of the widespread or commercial introduction of Genetically Modified Organisms (GMOs) into the environment, and what are the implications for policy and regulation of GMOs?

It is now widely recognized that the term "genetically modified organism" (GMO) in reality consists of two major classes of organisms, namely:
- *Genetically modified organisms,* where a physiological or biochemical intervention has been performed on an organism to change, alter or modify its genetic character to a point where it is genetically distinct (i.e. different) from the original (parent) organism, endowing it with the ability to exist under certain (different) circumstances, or to increase its ability to produce desirable characteristics or products; and
- *Genetically enhanced organisms*, where a physiological or biochemical intervention has been made that does not alter the organism's basic genetic make-up, (i.e. it is considered to be a variety of the parent organism, rather than genetically distinct from the parent organism), but rather seeks to improve or increase one or more of its existing attributes, such as its ability to produce larger crop yields, synchronize its production of seeds or other desirable properties.

Whilst these differences may appear to be slight, they represent quite dramatic differences in terms of their "acceptance" or "desirability" amongst stakeholders.

To date, The Water Research Commission has not funded any research in the arena of genetically modified organisms – possibly because most genetically modified organisms are associated with terrestrial activities – such as food security, rather than the water sector. Nevertheless, these organisms have both direct and indirect implications for the water sector, for example through their water requirements and through the possible entry of genetically modified organisms into the riparian zones of rivers. Typical cases would be the accidental (or deliberate) release into riparian zones of new varieties of trees grown for wood and paper production, as well as new varieties of crop plants. In this type of situation, these organisms could become regarded as "super weeds" that could threaten the biological integrity of riparian and aquatic ecosystems. Their requirements for nitrogen, phosphorus or other nutrients would alter patterns of nutrient availability and exert additional restrictions on the indigenous species present.

Several concerns have been expressed about the adverse consequences of using genetically modified organisms; these range from moral and ethical considerations through to ecological, physiological and economic matters. The complex nature of these concerns means that their proponents will not be easily placated by traditional, purely scientific approaches. Instead, resolution of conflicting standpoints will require stakeholders to engage in participative processes, where clear and unambiguous scientific evidence can be provided to assist with decision-making. The Water Research Commission can play a leading role within the water sector by enabling and co-ordinating research efforts that are designed to provide unequivocal evidence on the water-related aspects of these organisms the debate. In turn, this will assist national authorities (e.g. the Department of Agriculture), that are charged with the primary responsibility for developing and implementing policy instruments related to the use of genetically modified organisms in South Africa.

A.3.2 Issue 18: Nuisance species

The research question for issue 18 is:

What is the extent and potential impact of nuisance species (terrestrial and aquatic; fauna and flora; alien and indigenous) on environmental functioning within the hydrological cycle?

The majority of the research relevant to this issue has been conducted in the tertiary catchments along the Orange River, and within the catchments of the Vaal and Olifants rivers (**Figure A33**).

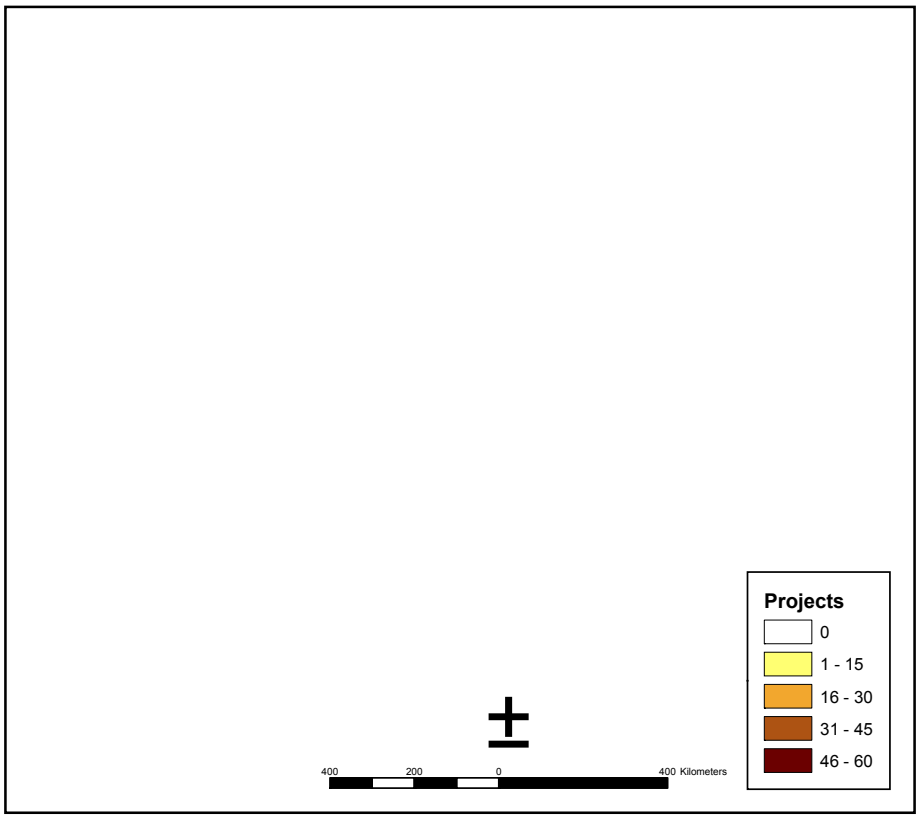


Figure A33: Tertiary catchment distribution of WRC research records relevant to issue 18 (n=21).

Research has primarily been undertaken at a national scale, at both situation assessment and process levels (**Figure A34**). At the catchment and site-specific scale, most of the research has focussed on process-orientated aspects. Relevant research has focused on the biological control of blackfly populations and algal blooms in dams and irrigation canals, and on invasive alien species and their impacts on water resources.

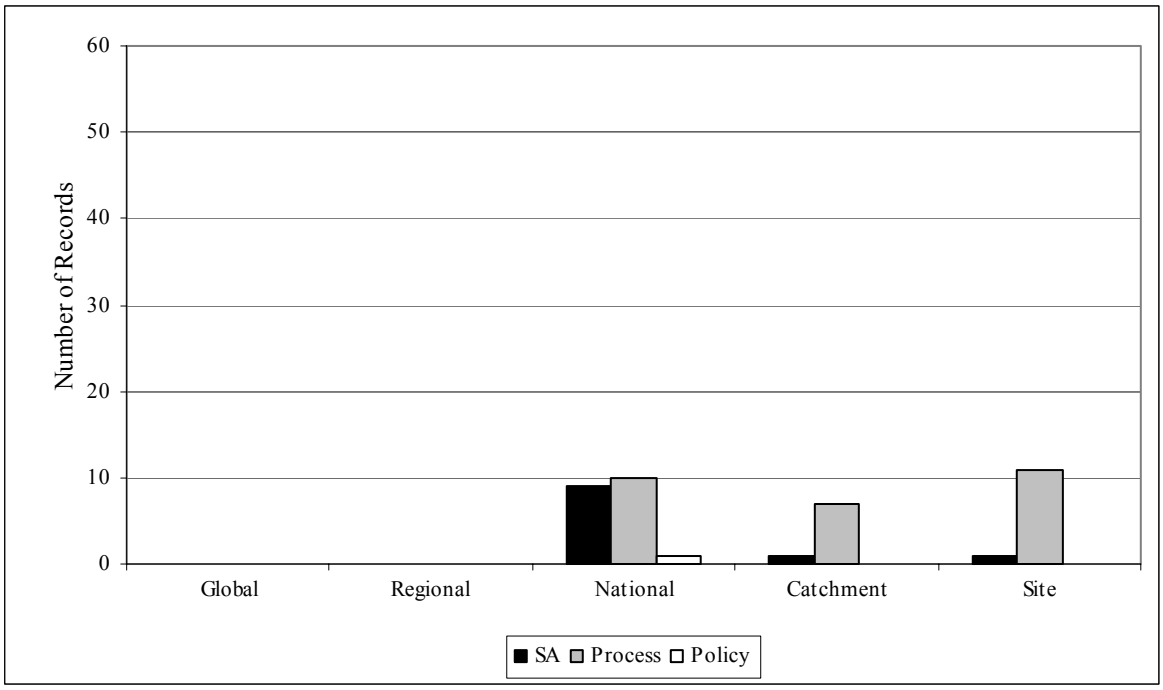


Figure A34: Number of WRC research records per level and scale of study relevant to issue 18 (n=36).

Whilst a considerable volume of research has been conducted on invasive alien and indigenous organisms over the last 35 years, the Water Research Commission has focussed it's funding strictly on those issues that have direct relevance for water resource management. One of the major concerns related to the numerous different research projects that have been conducted on behalf of several different funding agencies, is that there appears to be a relatively limited degree of co-ordination between the various funding bodies. This has, in some cases, hampered proper consolidation and integration of national efforts to control invasive species and reduce their effects on the country's terrestrial and aquatic ecosystems.

This situation can be resolved by conducting a thorough overview of all efforts directed at or linked to invasive species, followed by a clear prioritisation of key issues of concern. This could then form the foundation for improved national strategy and policy, as well as a basis for enhancing collaboration between the different funding agencies and research teams. Here, the Water Research Commission could play a pivotal leadership role within the water sector, acting as a knowledge broker. This would also help to improve the transfer of knowledge and technologies across South Africa as well as to our SADC neighbours.

A4. Programme 4: Interfaces

Programme 4 comprises 4 issues, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

Programme 4 issues:
- Freshwater requirements of the nearshore marine zone;
- Impacts of deep groundwater abstraction;
- Impacts of artificial recharge; and
- Role of Groundwater Dependent Ecosystems (GDEs) in regulating processes in the hydrological cycle.

A.4.1 Issue 19: Freshwater requirements of the nearshore marine zone

The research questions for issue 19 are:

What is the contribution of freshwater, derived from land, but not delivered through river mouths or estuaries, to the nearshore marine zone? What is the ecological significance of this contribution? What are the implications for water resources management?

None of the research projects funded by the Water Research Commission are considered to provide insights into this issue.

In South Africa, very little research has been directed towards understanding and quantifying the freshwater contribution that enters near-shore marine zones as a result of direct (groundwater) flows from the terrestrial areas located between river mouths and estuaries. This freshwater contribution is particularly important in the higher rainfall (equatorial) regions of Central and West Africa, and may also be important along the wetter south-eastern coastal zone of South Africa. Some research has been conducted to evaluate the extent and significance of freshwater contributions from river mouths and estuaries; this needs to be extended to improve our understanding of the extent and significance of groundwater contributions. In turn, this will help to improve our understanding of the water balance of coastal catchments and the implications of land-based activities for near-shore ecosystems, whilst also improving our ability to reduce the potentially adverse consequences of materials derived from terrestrial activities on sensitive coastal ecosystems.

A.4.2 Issue 20: Impacts of deep groundwater abstraction

The research questions for issue 20 are:

What are the distribution and the current & projected utilisation of deep (>500m) groundwater bodies in South Africa? What are the potential impacts (geochemical, geohydrological, ecological) of deep (>500m) groundwater extraction on the components of the hydrological cycle, and on environmental functioning within the hydrological cycle? What are the implications for policy and regulation?

Very little research has been undertaken in this field of study. Those areas where research has been undertaken are located within tertiary catchments along the coast, and within sections of the Orange, Vaal and Olifants catchments (**Figure A35**).

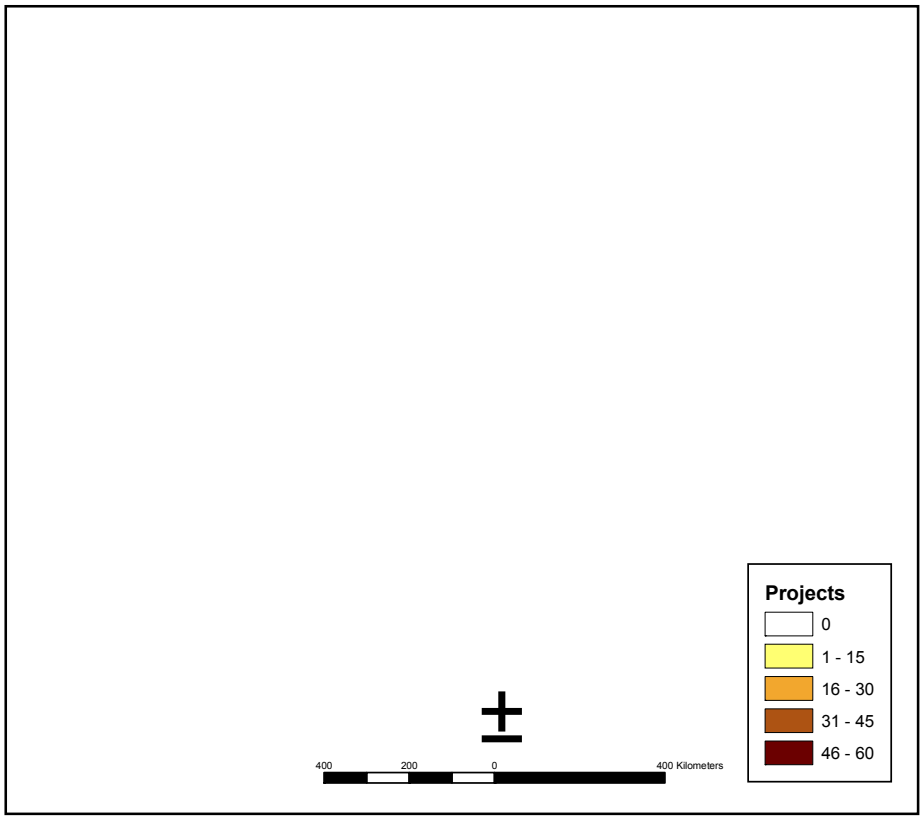


Figure A35: Tertiary catchment distribution of WRC research records relevant to issue 20 (n=29).

The majority of the research has been site-specific and process orientated (**Figure A36**), with some policy related research being conducted at both national and site-specific scales. The research that has been undertaken includes mine dewatering studies, groundwater-surface water interactions, groundwater abstraction and groundwater quality for agriculture and human consumption.

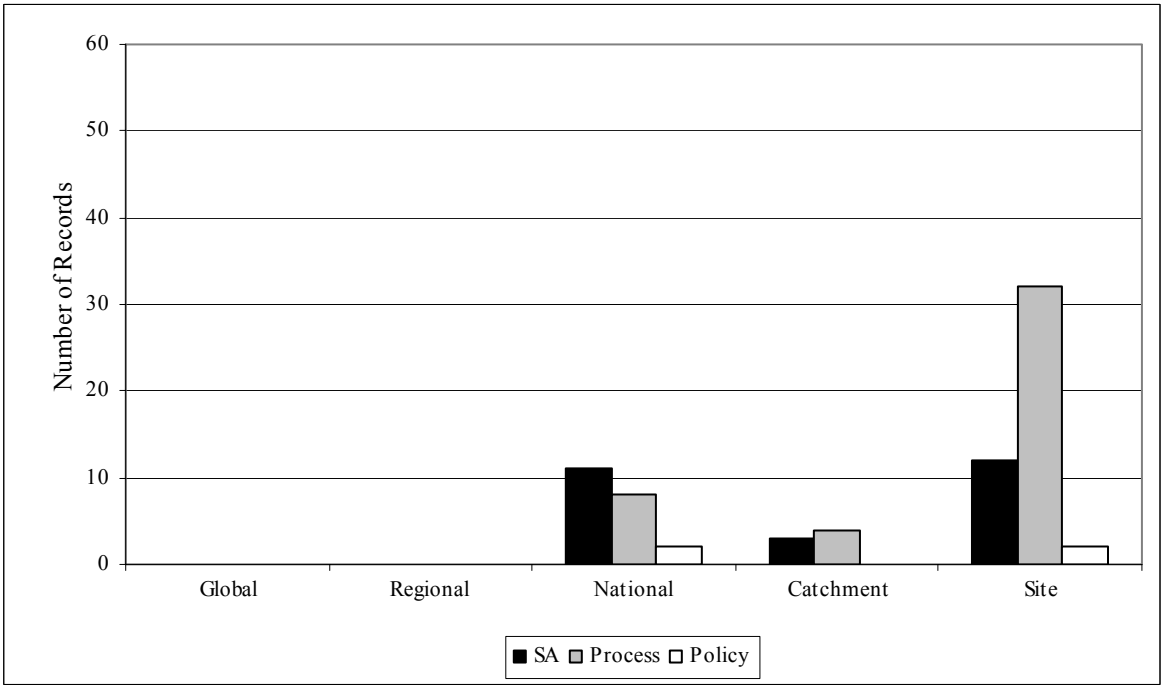


Figure A36: Number of WRC research records per level and scale of study relevant to issue 20 (n=69).

Deep sources of groundwater are currently under-exploited as sources of water for human use in South Africa and very little information is available on the quantity, quality and reliable yield of these sources, upon which to base management decisions. In turn, this prevents proper planning and also reduces opportunities for incorporating the water from these sources into the national water balance.

Future research is needed to understand the role of deep groundwater sources on the subterranean, terrestrial and aquatic components of the water cycle, and determine the extent to which these resources may be exploited sustainably. This will then form the basis for the development and implementation of appropriate policy instruments. Once again, the Water Research Commission can play a leading role in directing and co-ordination national research efforts in this arena.

A.4.3 Issue 21: Impacts of artificial recharge

The research questions for issue 21 are:

To what extent do artificial recharge practices impact on biochemical, geochemical, hydrological and ecological processes within the hydrological cycle? What are the implications for policy and regulation?

Research relevant to this issue has been conducted in the arid/semi-arid regions of South Africa, especially in the Northern Cape, the northern KwaZulu-Natal coast, the mining areas along the Vaal River, and sections of the Olifants catchment (**Figure A37**).

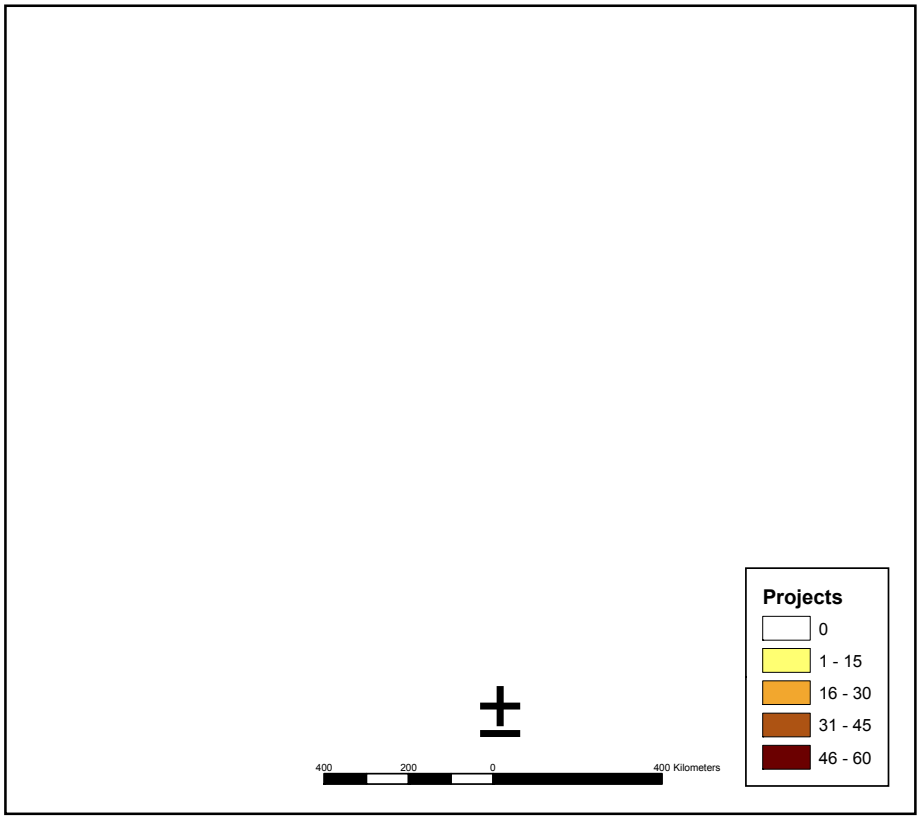


Figure A37: Tertiary catchment distribution of WRC research records relevant to issue 21 (n=25).

Site-specific studies predominate the research that has been conducted to date, with process-orientated research being the most common (**Figure A38**). Some research has also been carried out at national and catchment scales, though to a lesser extent, and this has focussed on situation assessment and process-orientated aspects. Much of the research undertaken to date has been directed towards mapping the groundwater resources of South Africa, refining the technologies for artificial recharge, and on estimations of the degree of groundwater recharge of aquifers.

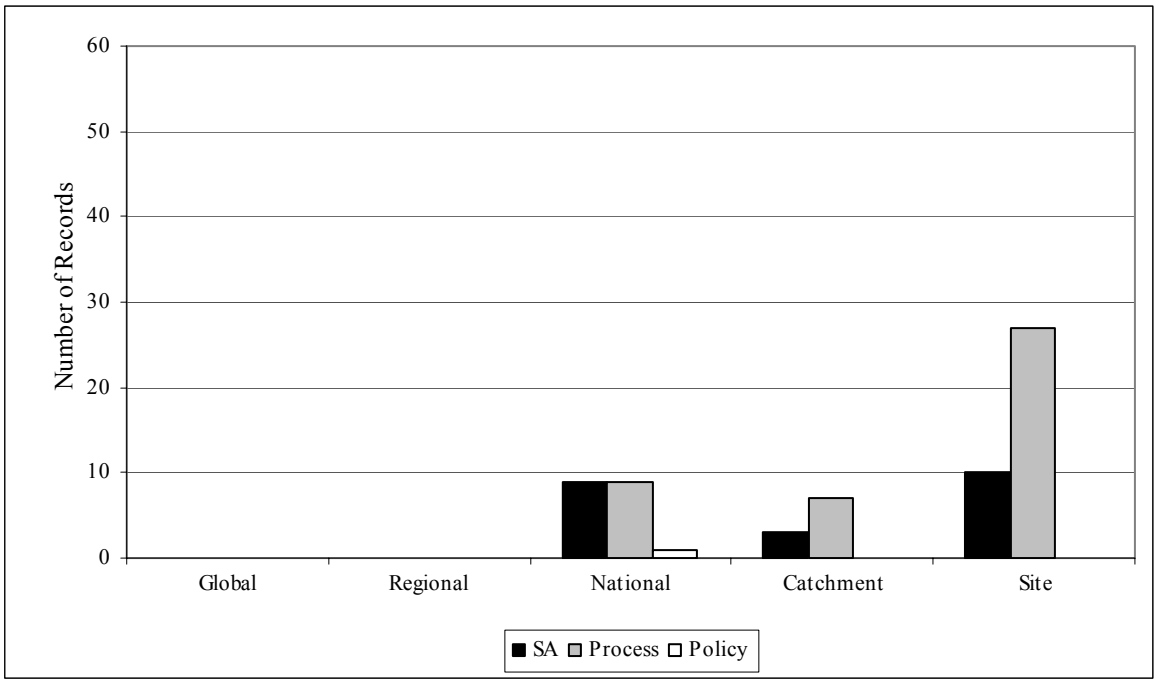


Figure A38: Number of WRC research records per level and scale of study relevant to issue 21 (n=61).

Artificial recharge of aquifers offers an excellent opportunity to increase the safe yield of aquifers that are used to supply water for human uses, and to minimize adverse ecological consequences associated with high rates of groundwater abstraction form shallow aquifers. This is particularly relevant for many communities and farming operations located in the more arid regions of South Africa where there is a very high degree of reliance on groundwater. However, whilst aquifer recharge offers great promise in terms of increased quantities of water, we lack detailed knowledge of the precise geophysical and geochemical changes that occur as a result of aquifer recharge. This poses the risk that adverse chemical changes could render the water unfit for its intended use or impose a requirement for expensive treatment prior to use.

There is therefore a clear need for improved understanding of all the processes involved in or affected by artificial aquifer recharge attempts, as a basis for the development of appropriate policy instruments. The Water Research Commission is ideally placed to provide leadership in this research arena and facilitate the process of policy development.

A.4.4 Issue 22: Role of GDEs in regulating processes in the hydrological cycle

The research question for issue 22 is:

What is the role of groundwater-dependent ecosystems (those contained within aquifers, as well as Karst and cave systems) in regulating ecological processes between components of the hydrological cycle?

Relatively little of the research funded by the Water Research Commission is relevant to this issue. The majority of the relevant research that has been conducted in the Vaal catchment, in isolated tertiary catchments in the Orange catchment, and along the coastal regions of South Africa (**Figure A39**).

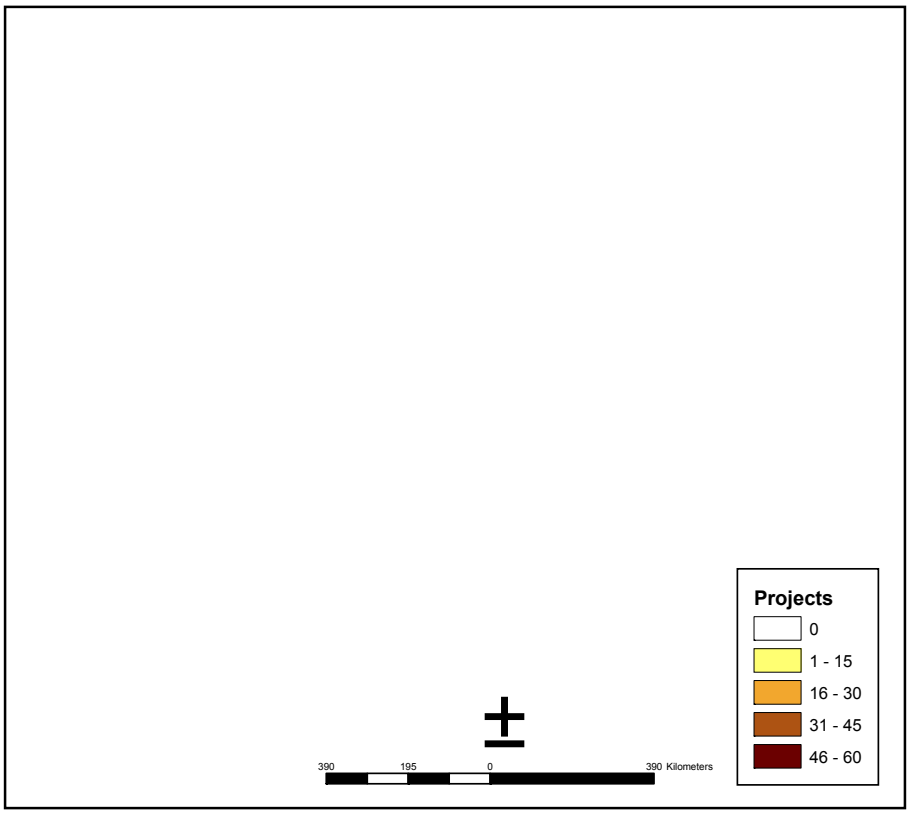


Figure A39: Tertiary catchment distribution of WRC research records relevant to issue 22 (n=22).

The most relevant research undertaken to date, has been the classification of groundwater dependent ecosystems for the groundwater component of the ecological reserve. Other useful studies include those aimed at improving our understanding of groundwater flows, groundwater recharge and aquifer storage capacities, and groundwater contamination. The majority of the research has been conducted at a site-specific level and is predominately process orientated research (**Figure A40**).

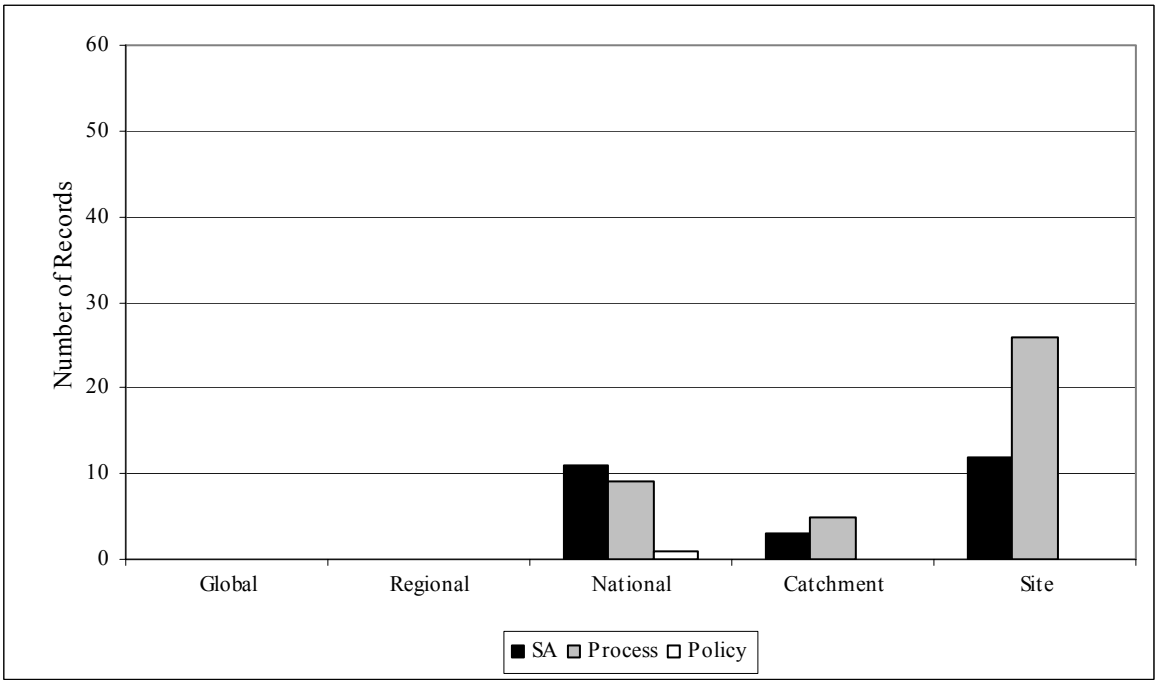


Figure A40: Number of WRC research records per level and scale of study relevant to issue 22 (n=61).

Several research projects have been carried out on those terrestrial ecosystems that depend on shallow groundwater aquifers for their survival. These have focussed particularly on riparian vegetation and on estimations related to the quantity of water required by these ecosystem components. Very little emphasis has been placed on the geochemical aspects of these waters, other than the type, degree and spatial extent of contamination that might occur as a result of inappropriate land-based waste disposal activities.

Shallow groundwater aquifers also play critically important roles in sustaining the base flow of river systems during the dry months of the year when no rainfall occurs. Any deterioration in either (or both) the quantity or quality of these groundwater sources will have highly significant consequences for dry season surface water flows in river systems. Here, the quality aspects of groundwater contributions to baseflow are also critically important in terms of the degree to which dry season flows remain fit for human use. Contamination of baseflow by agricultural return flows or other forms of wastewater pose significant challenges for water resource managers.

In addition, shallow groundwater aquifers are often the only source of water able to sustain riparian vegetation along seasonal and ephemeral rivers in the arid regions of southern Africa. These shallow aquifers are normally recharged during the infrequent rainfall and resultant runoff events that characterize these regions. If some or all of this runoff is intercepted and then recharged to deeper aquifers, shallow aquifers that rely on local runoff for their recharge will become progressively desiccated and unable to supply the water requirements of their riparian vegetation. In turn, this will hamper the sustainable management of these seasonal and ephemeral river systems.

The Water Research Commission is ideally placed to provide a strong leadership role for the water sector in this research arena, and to support national policy development efforts.

A5. Programme 5: Resource directed measure (RDM)

Programme 5 comprises 3 issues, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

Programme 5 issues:
- Climate change and IFR policy;
- Instream water quality criteria for aquatic ecosystems; and
- Ecological functions in IFR determination models.

A.5.1 Issue 23: Climate change and IFR policy

The research questions for issue 23 are:

What are the implications of climate change for the philosophical basis of in-stream flow requirements (IFRs) of aquatic ecosystems and the Reserve, the methodologies currently used to determine IFRs, and the status of existing environmental flow allocations? What are the options for policy responses?

Research studies that are pertinent to this issue have been undertaken along the Orange River, within those sections of the Olifants and Crocodile catchments that fall within the Kruger National Park, and within sections of the uMngeni and Phongolo catchments in KwaZulu-Natal (**Figure A41**).

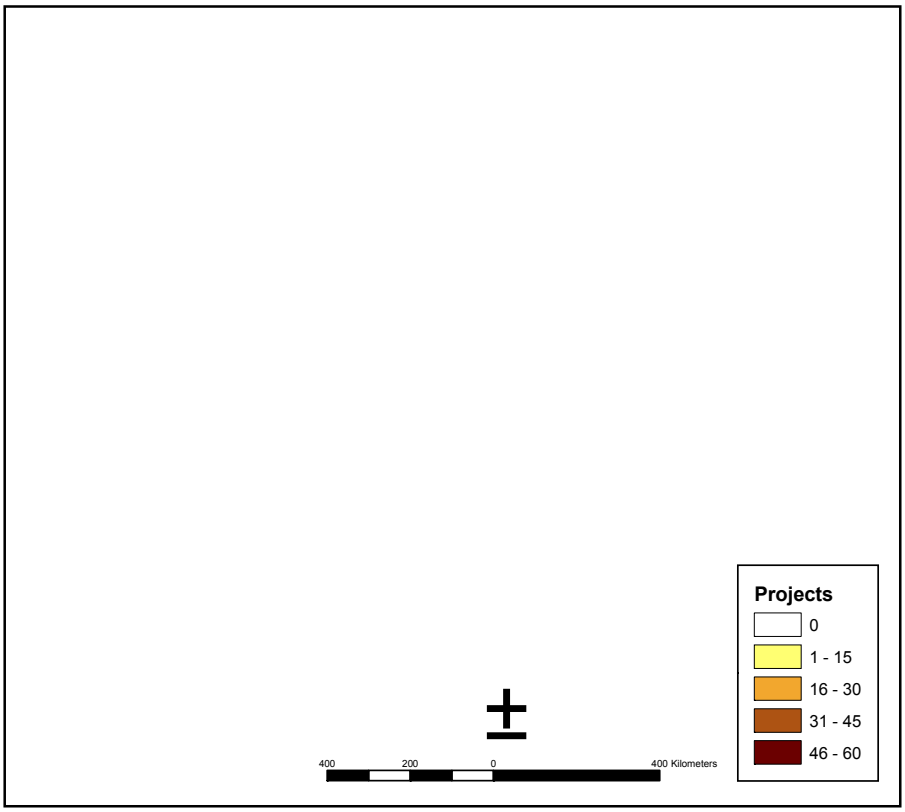


Figure A41: Tertiary catchment distribution of WRC research records relevant to issue 23 (n=33).

The majority of studies have been undertaken at a national scale and were conducted at all levels of research (**Figure A42**). Process orientated research has dominated national, catchment and site-specific studies, with policy research receiving modest levels of attention at national and catchment scale. The focus of the research undertaken includes estimations of streamflow reductions due to various landuses, techniques to support the determination of the water quality and quantity components of the ecological reserve, methodologies for instream flow assessments, and understanding of ecosystem dynamics.

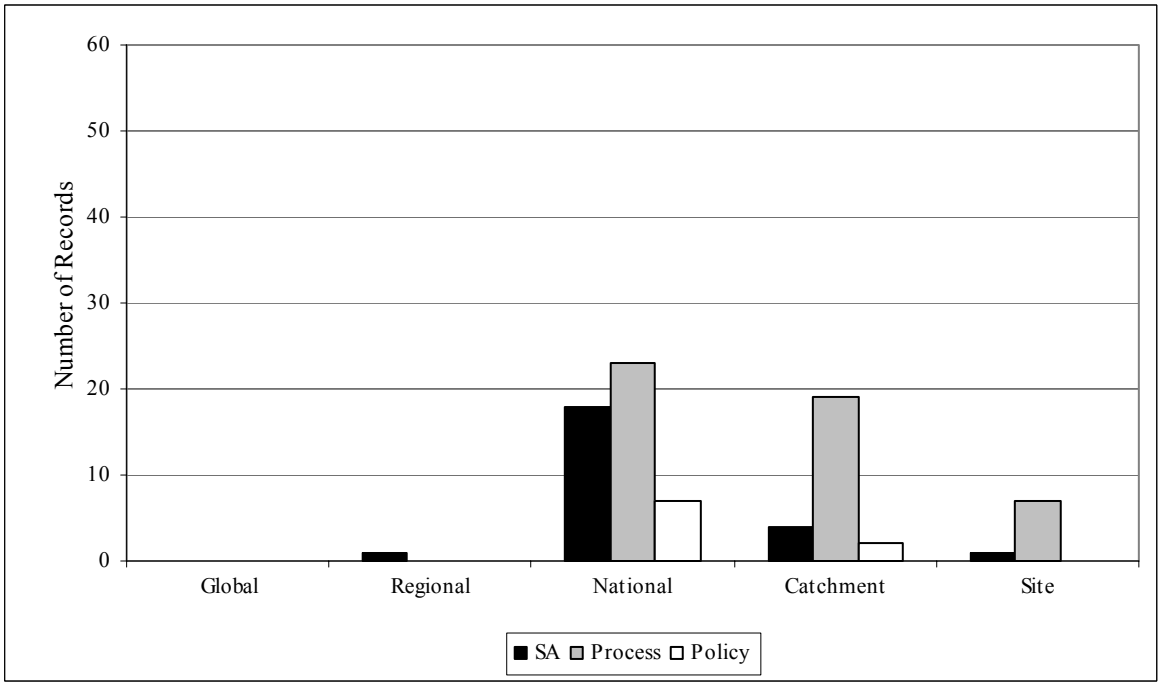


Figure A42: Number of WRC research records per level and scale of study relevant to issue 23 (n=71).

The anticipated effects of global climate change could cause important changes to the hydrology of southern Africa and, if these occur as anticipated, they will likely affect every component of the hydrological cycle. If these changes do indeed occur, they will have important consequences for assessments of the quantities of water and patterns of flow that are required to sustain aquatic ecosystems as a central part of the "Reserve". In particular, if the flow patterns or hydrological characteristics of a river change as a result of climate change, this could alter the philosophical basis of in-stream flow requirement methodologies, as well as hampering the practical execution of such assessments for aquatic ecosystems. In turn, this would cast doubt on the applicability and relevance of the quantities of water recommended by those in-stream flow requirement studies that may have already been carried out in priority catchments.

If the above observations are indeed valid, there will be a need for careful evaluation of the underlying philosophy of in-stream flow requirement methodologies, followed by a clear policy level response that will guide current and future assessments of the flows required to sustain aquatic ecosystems. Once again, the Water Research Commission is ideally placed to play a strong leadership and co-ordinating role within the water sector; first by directing a comprehensive review of the methodologies used, and then evaluating the likely consequences of potential climate change scenarios.

A.5.2 Issue 24: Instream water quality criteria for aquatic ecosystems

The research question for issue 24 is:

What are the strategic research issues and key knowledge gaps related to the derivation of in-stream water quality criteria for aquatic ecosystems (freshwater and estuarine)? How should these be addressed?

The tertiary catchments located along the coast of South Africa, as well as a few tertiary catchments within the Orange, Vaal and Olifants primary catchments, have provided the basis of research undertaken that is relevant to this issue (**Figure A43**).

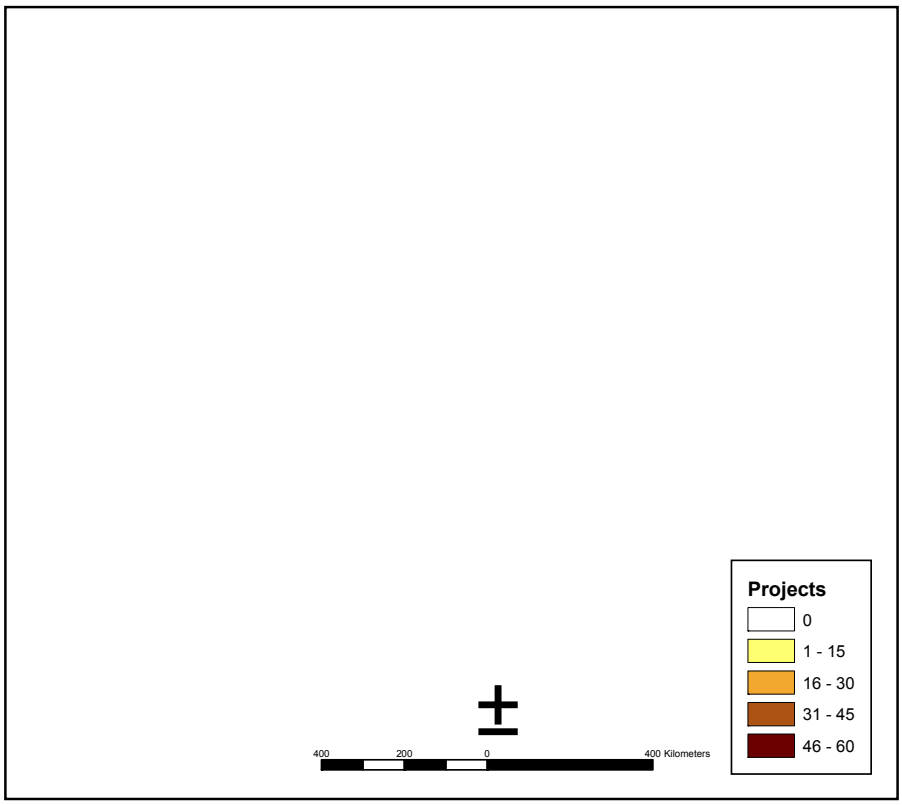


Figure A43: Tertiary catchment distribution of WRC research records relevant to issue 24 (n=54).

The focus of research has been primarily on understanding the relationships between hydrological processes and water quality, predicting selected water quality characteristics in ecological reserve determinations, understanding the requirements of ecosystems in terms of key water quality characteristics, and assessing the potential impacts of reduced water quality due to pollution. The majority of the research has been undertaken at a national scale, although studies at catchment and site-specific scales have also received much attention, particularly at a process level (**Figure A44**). Situational assessment studies have been undertaken from a national scale to a site-specific scale, as has policy related research.

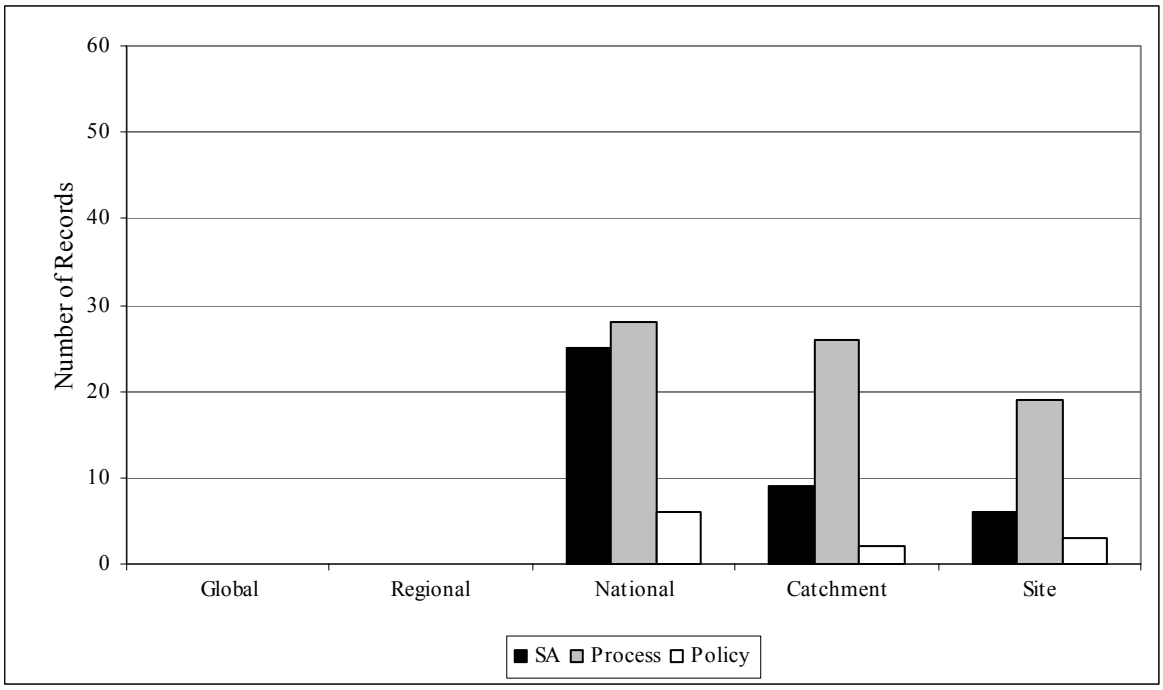


Figure A44: Number of WRC research records per level and scale of study relevant to issue 24 (n=111).

The original "trigger" for research in this arena was the emphasis placed on the development of water quality guidelines for freshwater aquatic ecosystems as part of the suite of water resource management "tools" being developed by the Department of Water Affairs and Forestry. At the time, this programme engaged a wide spectrum of aquatic scientists and researchers and culminated in the production of the first edition of South Africa's series of water quality guidelines. Since then, however, interest has tended to wane and few researchers are still active in this field, with very little new capacity being developed.

Originally, the water quality guidelines placed greatest emphasis on inorganic constituents and very little attention was paid to organic constituents. Given the appearance of growing numbers of novel organic compounds each year, it is also clear that our ability to undertake the necessary analyses for these substances is also declining or is constrained by the high costs of such analyses. Parallel attempts to circumvent these problems concentrated on the use of bioassay techniques that sought to use different types of toxicity assessment as criteria for acceptable or unacceptable levels of contamination in water. Whilst these efforts continue today, they too have been scaled down.

One of the most important gaps in knowledge is caused by the absence of water quality guidelines for estuaries. The available guidelines for freshwater systems and marine water quality guidelines are both inappropriate for use in estuaries. This has hampered our collective efforts to manage the water quality of South Africa's estuaries. The Water Research Commission is considered to occupy a leadership position within the water sector and would thus be the ideal organization to co-ordinate national research efforts that aim to consolidate our knowledge and assist with the development and implementation of appropriate policy instruments.

A.5.3 Issue 25: Ecological functions in IFR determination models

The research question for issue 25 is:

Current methods for determination of IFR take little or no account of important ecosystem processes related to the integrity, functioning and resilience of those systems (e.g. oxygenation, metal sequestration, nutrient cycling, sediment-water interactions and sediment quality). How should/could existing and emerging methodologies be adapted to integrate these aspects into IFR determinations?

The majority of studies that are relevant to this issue were undertaken in the tertiary catchments of the Sabie River within the Kruger National Park, in small and large rivers along the coast of South Africa, along the Orange River, and within the Olifants, Thukela and uMngeni catchments (**Figure A45**).

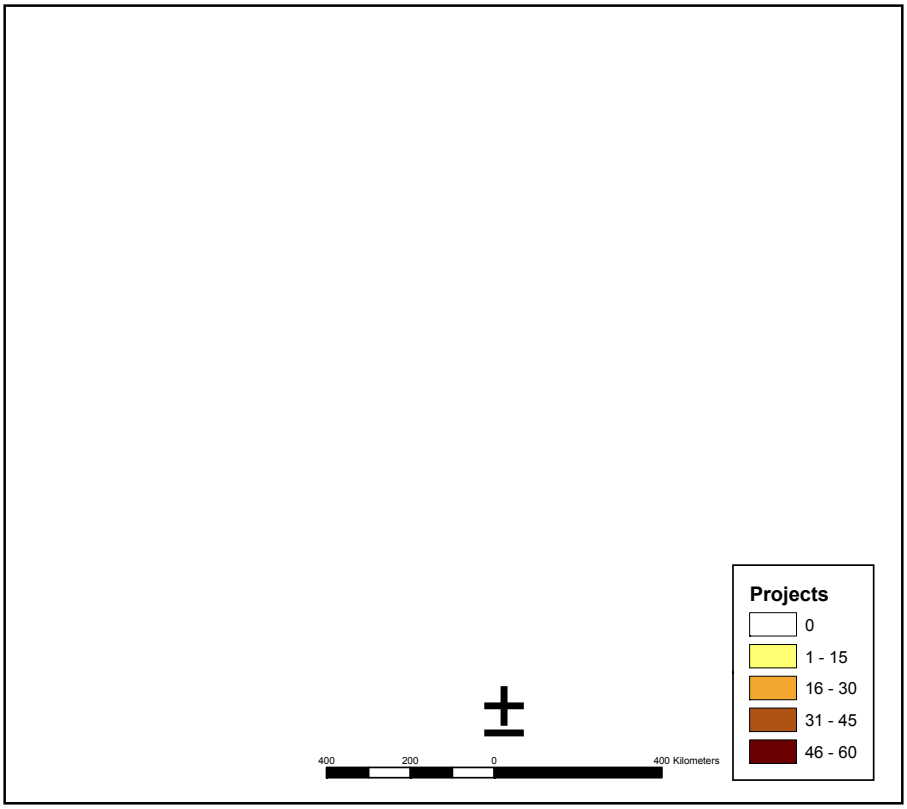


Figure A45: Tertiary catchment distribution of WRC research records relevant to issue 25 (n=50).

Relevant research has primarily been conducted at the national scale, at all three levels of research (**Figure A46**). Across these scales, process orientated research has dominated, while policy research has received the least attention. Research that is relevant to this issue includes studies on instream flow requirement methodologies, understanding ecosystem processes especially riparian and estuarine components, indicators for catchment management, and water quality indices of environmental health.

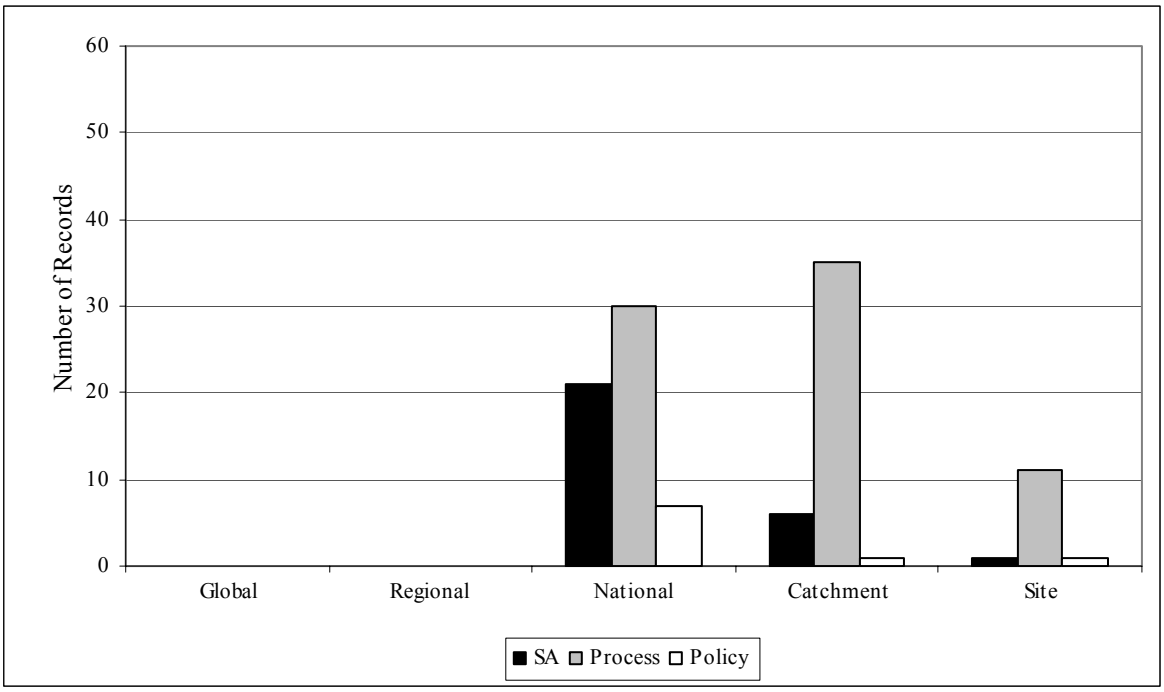


Figure A46: Number of WRC research records per level and scale of study relevant to issue 25 (n=101).

Currently, in-stream flow requirement methodologies are based on simplified considerations of biodiversity that concentrate on the structural and (sometimes) compositional aspects of biodiversity. These tend to ignore important functional attributes of biodiversity with the result that key ecological processes are often not included, or are considered to be represented by some surrogate measure linked to the presence or absence of key indicator species (see Issue 16). Whilst this is a pragmatic approach, it omits consideration of these key processes and consequently is unable to provide useful information on the degree of integrity, resilience or vulnerability of aquatic ecosystems to potential external changes. This is clearly an undesirable situation and needs to be remedied if estimates of ecological in-stream flow requirements are to have proper relevance in water resource management approaches.

The Water Research Commission has recently initiated a comprehensive review of current methodologies that are used as indicators of biodiversity in aquatic ecosystems, with the intention of using this as a foundation for the development of indicators that more fully reflect the structural, compositional and functional attributes of biodiversity. This review will pay particular attention to ecosystem-level processes that are needed to provide researchers and decision-makers with appropriate information on the extent to which aquatic ecosystems are able to continue to deliver the ecosystem services, goods and benefits that are needed of them.

A6. WRC Strategic Issues

At this time, the WRC strategic issues focus on two concerns, the abbreviated titles of which are listed below (see **Table 1** for description of programme and **Table 6** for full descriptions of issues).

WRC Strategic Issues:
- Impacts of national, regional and NEPAD poverty alleviation policies and strategies; and
- Implications of HIV/Aids scenarios for water use and water resources management.

A.6.1 Issue 26: Impacts of national, regional and NEPAD poverty alleviation policies and strategies

The research question for issue 26 is:

What are the potential impacts of national, regional and NEPAD poverty alleviation policies and strategies on the hydrological cycle, and hence on the availability, quality and reliability of water resources?

Research that is relevant to this issue has been undertaken within the primary catchments of the Vaal, Limpopo and Olifants rivers, as well as along the coast of South Africa (**Figure A47**).

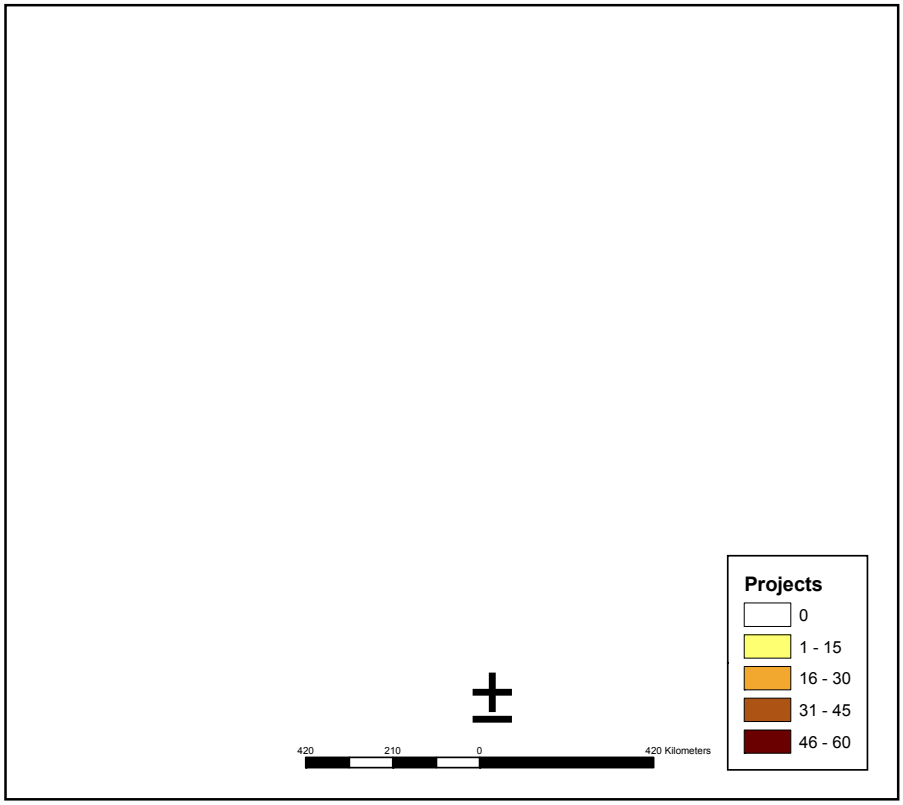


Figure A47: Tertiary catchment distribution of WRC research records relevant to issue 26 (n=43).

Many research studies could provide some background information that would enable new insights to be derived in support of answers to this research question. Those studies that were relevant include: stakeholder participation in water resources management, water supply evaluations, rural water supply and sanitation projects, grey-water management and water treatment processes. The majority of the relevant research has been conducted at national, catchment and site-specific scales, with major emphasis on process level research (**Figure A48**). Research that supports policy, or is policy-related, has received some attention at the national scale, with less attention at the site-specific scale.

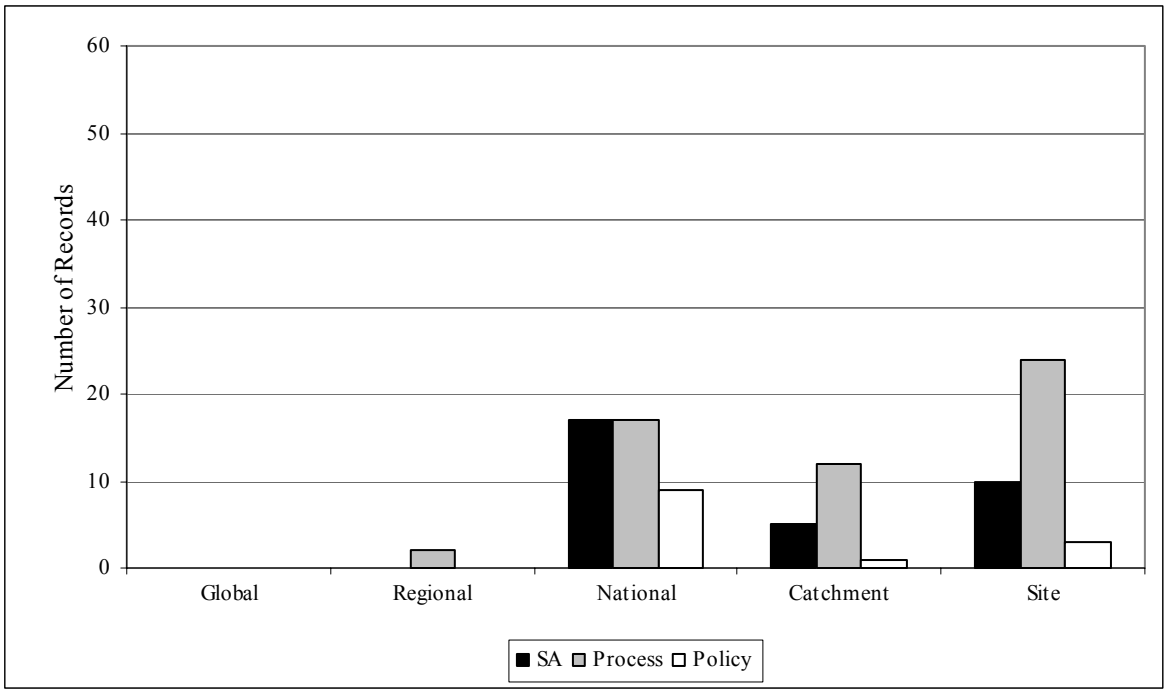


Figure A48: Number of WRC research records per level and scale of study relevant to issue 26 (n=90).

Virtually every research project initiated by the Water Research Commission can provide (or already has provided) some information that is relevant to this issue. However, there is no accepted country-wide assessment, or assessments directed at specific development nodes, that can provide unequivocal answers to all aspects of the questions posed above. This hampers South African efforts to provide fully appropriate leadership in SADC and NEPAD efforts to alleviate poverty and attain the Millennium Development Goals. The pressing need to implement poverty alleviation measures and improve the quality of life of previously disadvantaged peoples has often meant that the impacts of the remedial measures are ignored. Clearly, this situation is not sustainable in the long-term and decision-makers will increasingly need to deploy impact mitigation or rehabilitation strategies to prevent long-term degradation of the country's water resources.

Clear and unambiguous information is needed at a national scale, as well as at catchment scales, to understand the likely future trajectories of water supply and demand, as well as the consequences for the quality of these resources. Several catchments in South Africa are already approaching closure and "new" supplies of water are not easily available or economically affordable. It will also be important to understand the different supply-side and demand-side management options that will need to be deployed to meet the future needs for water on a sustainable basis. In particular, greater certainty is needed around our ability to predict the areas where new or expanded developments will occur, and when this will likely take place. In turn, this information will need to be incorporated into the country's longer-term planning process and used to derive appropriate water resource management strategies.

A.6.2 Issue 27: Implications of HIV/Aids scenarios for water use and water resources management

The research question for issue 27 is:

What are the implications of HIV/AIDS scenarios for water use and water resources management (quantity and quality)?

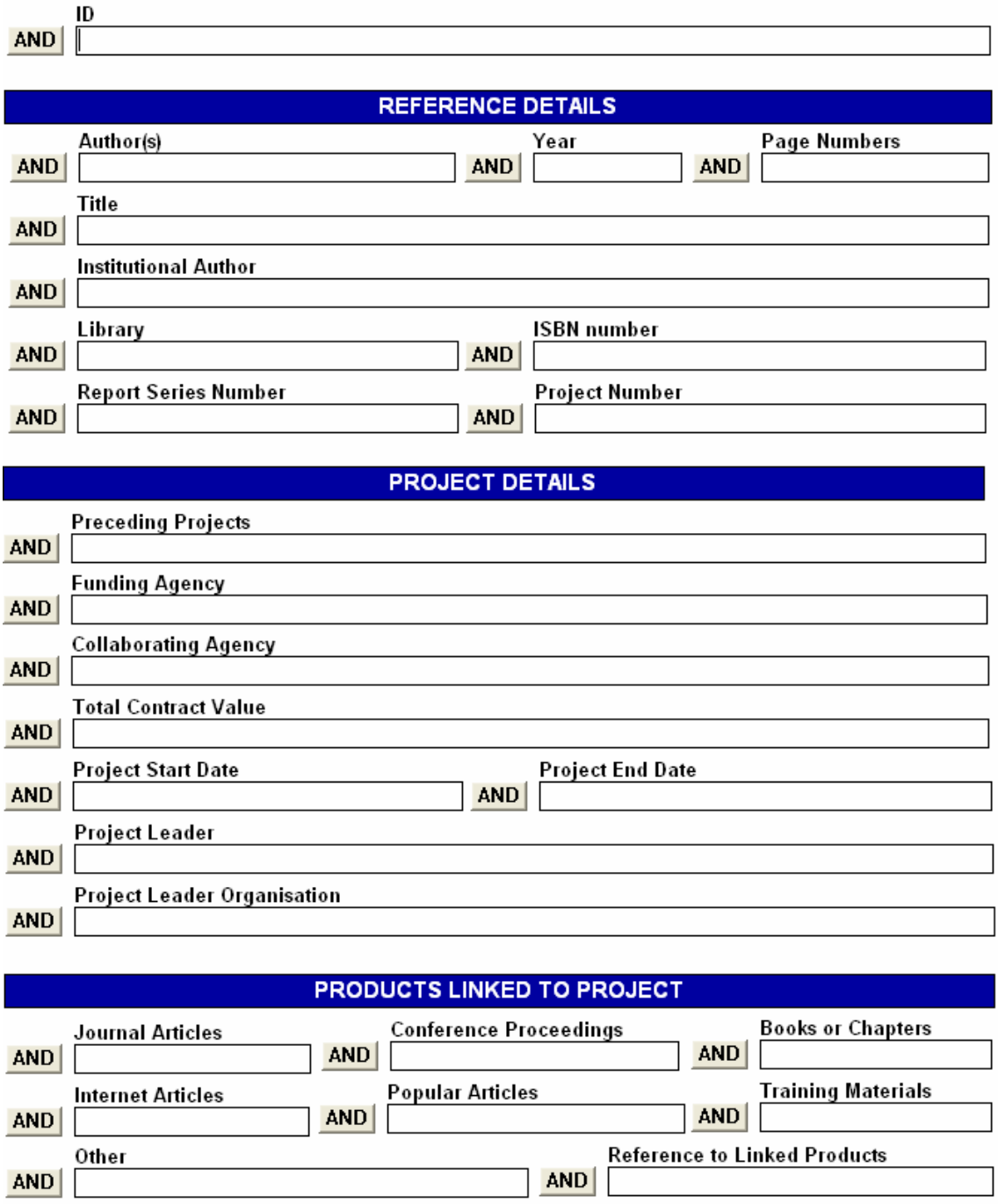
To date, the Water Research Commission has not funded any research into the implications of the South and southern African HIV/Aids pandemic for the quantity and quality of the country's water resources, or their management.

Other studies have provided initial evidence that the HIV/Aids pandemic has had, and will continue to have, extremely serious implications for the entire water sector and for water resources management throughout the SADC region. Amongst the typical implications are:

- People with compromised immune systems are also vulnerable to poor water quality and can more easily contract a wide variety of water-borne diseases if they are supplied with water of a sub-standard quality;
- Rural people who have to walk long distances to fetch water face increased risks of water deprivation if they are weakened by HIV and/or Aids – they will find it increasingly difficult to meet their daily water needs. Where these communities have to rely on water of uncertain or dubious quality, their plight is worsened;
- Inaccurate estimates of population numbers and population growth rates hamper proper planning of new water supply schemes – the time lag between initiating (conceptualising) and completing (commissioning) a large water supply scheme may mean that fewer people than anticipated will be present when the scheme comes on line;
- Since HIV/Aids tends to have greatest effects on the younger, more economically active and mobile members of the population, tending to spare the elderly and very young, the "survivors" may not be able to afford to pay for service delivery when such services are finally delivered.

It is important to note that a far wider suite of consequences than those listed above, is already occurring. The pressing urgency of the situation is reflecting in the enormous numbers estimated for HIV/Aids prevalence in several southern African countries. The Water Research Commission is ideally placed to lead and direct a national effort that would examine the available evidence and provide an unequivocal evaluation of the current and future situation of the pandemic, as well as firm policy recommendations for urgent implementation within the water sector. This would also contribute to the development of appropriate national and regional (SADC) policies and strategies.

APPENDIX B: DATABASE TEMPLATE



PROJECT INFORMATION

AND Cross-cutting Domain Issue

AND Hydrological Cycle Component

LEVEL OF STUDY

AND Situation Assessment

AND Situation Assessment Comment

AND Process Research

AND Related Processes

AND Process Comment

AND Policy Response

AND Policy Comment

SCALE OF STUDY

AND Global Scale

AND Regional Scale

AND National Scale

AND Catchment Scale

AND Site Specific

LOCATION DETAILS

AND Study Area

AND River

AND Tertiary Catchment Numbers

OTHER

AND Keywords

AND General Comment

APPENDIX C: MASTER LIST OF KEYWORDS

Primary Keyword	Synonyms					
<500m						
>500m						
agreement	treaty	protocol	convention			
agriculture						
Aids	HIV					
air quality						
aquaculture						
artificial recharge						
benthos	benthic					
biodiversity	composition	structure	function	scale	organisational	
climate change						
climate variability	seasonality	predictability				
control						
desertification						
downstream impact						
dryland						
emission	seepage	leachate	discharge			
environmental water requirement	instream flow requirement					
estuary						
eutrophication						
evaporation						
fisheries						
flow regulating structure	dam	reservoir	weir			
forecast						
forestry						
formal						
geohydrology						
geomorphology						
GMO	genetically modified organism	genetically selected organism	genetically enhanced organism			

governance						
greenhouse gas						
groundwater						
hydrology	hydrological characteristic					
IBT	interbasin transfer					
indicator						
industry						
infiltration						
informal						
inorganic	TDS	TSS				
ionosphere						
irrigation						
IWRM	WRM					
lake						
land use						
legislation	regulation	law	Act	Bill		
limnology						
littoral						
livestock						
management						
MDG	Millennium Development Goals					
metal sequestration						
migration						
mining						
natural						
nearshore						
NEPAD	NePAD					
nitrogen cycling						
nuisance species	alien	indigenous	invasive	non-invasive	escaped	introduced
nutrient	inorganic nitrogen	inorganic phosphorus				
nutrient cycling						
objectives	standards	guidelines	criteria			

ocean current						
offshore						
oxygenation						
palaeontology						
peri-urban						
persistent inorganic pollutant						
persistent organic pollutant						
phosphorus cycling						
port						
potable						
poverty alleviation						
radioactivity						
reserve						
resource economics						
riparian						
riverine						
Rural						
SADC						
salinisation						
salinity	saline pans					
sanitation						
sediment quality	sediment chemistry					
sedimentation	sediment erosion	sediment transport	sediment deposition			
settlement						
sewage	sewerage					
stratosphere						
system variable	temperature	pH	dissolved oxygen			
temperature						
toxic	Al; As; Cd; Cu; F-; Hg; Mn; NH4+					
transboundary	shared river basin					
transpiration						
troposphere						
upstream impact						

Urban						
urbanization						
waste						
water quality						
water quantity	water use	water supply				
wetland						