Assessment of completed ecological water requirement studies for South African estuaries and responses to changes in freshwater inflow

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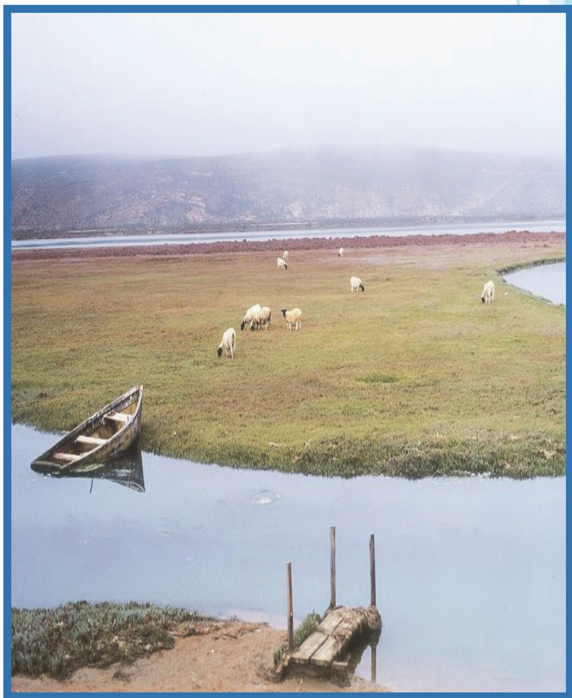

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Glossary

Abiotic: The non-living chemical and physical factors in the environment.

Catchment area: An area drained by a river or a body of water.

Ecological Class: Defines the condition in which each resource will be managed.

Ecological Reserve / Ecological Water Requirements: The quality, quantity and timing of freshwater inflows reserved to support ecosystem function.

Environmental Flow Assessment: The process of determining the amount of water that should purposefully be left in a river or be released from an impoundment in order to maintain a river in a desired state.

Estuarine Health Index: An overall assessment of the condition of estuaries.

Preliminary Reserve: The determination of an initial reserve until such time as the resource can be properly classified.

Present Ecological Status: The present quality (water quantity, water quality, habitat and biota) of the resource – assessed in terms of the degree of similarity to the reference condition.

Recommended Ecological Category: The category allocated is the target for protection and management of the resource. The category could be the same as PES or higher if an improved condition is desired.

Reference Condition: The natural, unimpacted characteristics of a water resource, and represents a stable baseline.

Resource Directed Measures: To ensure the protection of water resources, by protecting ecosystem functioning and maintaining a desired state of health of aquatic and groundwater dependent ecosystems.

Resource Quality Objectives: The setting of environmental flows and specific goals for the quality of the resource. Socio-economic: Indicators/studies looking at both social and economic conditions relevant to well-being.

Acronyms

CERM	Consortium for Estuarine Researchers and Managers
DWA	Department Water Affairs (Name change applicable after April 2009)
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Ecological Category
EFR	Environmental Flow Requirement
EHI	Estuarine Health Index
EMP	Estuary Management Plan
EWR	Ecological Water Requirements
KZN	KwaZulu-Natal
MAR	Mean Annual Runoff
NBA	National Biodiversity Assessment
NWA	National Water Act
PES	Present Ecological Status
POE	Permanently Open Estuary
RDM	Resource Directed Measures
REC	Recommended Ecological Category
RQO	Resource Quality Objective
TOCE	Temporarily Open / Closed Estuary
WMA	Water Management Area
WWTW	Waste Water Treatment Works

Summary

Freshwater abstraction for human activities threatens the health and provisioning of ecosystem services supplied by aquatic ecosystems. Estuaries are sensitive to a reduction in freshwater inflow, which is the main driver of their dynamic, variable nature. Input of discharge from waste water treatment works and agricultural return flow can result in increased freshwater inflow to estuaries. Ecological Water Requirements (EWR), also referred to as Ecological Flow Requirements, quantifies the water regime (quality, quantity and timing) required to ensure the adequate functioning and future persistence of estuaries. Estuaries are unique (e.g. shape, size, protection from wave energy) and have different responses to altered freshwater inflow. Thus studies of individual systems need to be undertaken. South Africa has been a forerunner worldwide for determining methods to assess EWRs. The South African Resource Directed Measures developed in 1999 in response to the National Water Act (Act 36 of 1998) has been consistently applied to different estuary types (permanently open, temporarily open/closed, river mouths, estuarine bays and estuarine lakes) in the country. To date studies have been conducted on 40% of South Africa's estuaries, although some studies are still ongoing. The majority (69%) of studies were completed as low confidence desktop or rapid levels. The classification of the Mvoti-Umzimkulu Water Management Area assessed 22% of South Africa's estuaries. The EWRs of half of South Africa's permanently open estuaries have been determined. Only three comprehensive reserve determinations have been completed. This report not only provides a summary of available EWR studies completed in South Africa, but also insights into the response of estuaries to altered freshwater inflow. It also highlights studies that have led to improved understanding of the freshwater requirements of estuaries. From the estuaries assessed the following lessons have been learnt:

1. Each estuary is unique in terms of its EWR.
2. Water can be released from dams to supply the EWR, but cannot mimic the entire natural flow regime.
3. Floods are needed to flush out and reset estuaries.
4. Increased flow, for example wastewater input or agricultural return flow, increases mouth breaching resulting in unstable conditions in temporarily open/closed estuaries.
5. Deterioration in water quality is a growing concern.
6. The importance of groundwater input to South African estuaries is unknown.
7. The offshore marine environment also has an EWR, but this does not form part of the current legal framework.
8. A catchment to coast integrated water management approach is necessary to ensure connectivity.
9. Co-operative governance is required to address non-flow related impacts and improve estuary health.
10. Field and long-term data are needed for high confidence EWR assessments.
11. Monitoring must take place in a strategic adaptive management cycle.
12. The tools developed to determine the EWR of an estuary are now being used to meet other legislative

Project objectives

The National Water Act (NWA) of South Africa (Act 36 of 1998) gives two rights to water, namely to basic human needs and to the protection of aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource. In terms of securing water for the protection of aquatic ecosystems, the Act requires the Classification of all water resources (including estuaries), accompanied by resource quality objectives (RQOs) that establishes clear goals relating to the quality of the relevant water resources. The Ecological Reserve, in turn, relates to the quantity and quality of river inflow required to protect the aquatic ecosystems of the water resource, which vary depending on the class of the resource. Recognising that the Classification process may take time, the NWA allowed for the preliminary determination of the Reserve for water resources and to this end the Department of Water and Sanitation (DWS, previously Department of Water Affairs and Department of Water Affairs and Forestry) developed *Methods for the preliminary determination of ecological water requirements.* In the case of estuaries these preliminary methods included the determination of the present ecological status (PES), ecological importance, the recommended ecological category (REC), a recommended ecological flow scenario, as well as ecological specification and monitoring programmes.

South Africa has been a forerunner in developing and applying methods to assess the EWR of estuaries. The EWR ensures the protection of aquatic ecosystems thus maintaining ecosystem services. Understanding the responses of estuaries to changes in freshwater inflow is particularly relevant in South Africa, which is a semi-arid developing country. The first method for assessing the preliminary EWRs for estuaries were developed in 1999 (Adams *et al.* 2002) and have been applied to 114 South African estuaries. Although there have been updates to the methods, the most recent in 2012 (DWA 2012), the overall approach has been the same thus allowing for a comparison of results. van Niekerk *et al.* (2012) evaluated the EWR from a hydrodynamic perspective but no single document exists that summarises the results from the studies conducted so far.

This is a unique opportunity to summarise and critically assess the completed EWR studies as South Africa is the only country in the world that has consistently applied the same method to a number of different estuary types (Adams 2012). There has been a significant investment by DWS in the conservation and management of estuaries in South Africa and it is timeous that a document is produced to highlight the achievements made. These data and insights have essentially gone unrecognised by the rest of the world, as the knowledge has not been integrated into unified reports for international publication. The project will also recommend a framework to capture EWR study data to be used in long-term monitoring and future studies by DWS, other consultants and specialists.

The aims of this study were to:

1. Compile and integrate the completed EWR studies for South African estuaries.
2. Critically assess past EWR studies for lessons learnt.
3. Collate and integrate available knowledge on the response of South Africa's estuaries to changes in freshwater inflow.
4. Develop a framework to capture data produced by ecological water requirement studies.
5. Promote South Africa's knowledge on the EWRs of estuaries globally.

Background

The demand for freshwater is continually increasing with the growth of human populations (Bengtsson *et al.* 2006). Almost half of the world's population live in coastal areas and as a consequence these areas have been altered by human activities (Borja & Dauer 2008). Advanced engineering has provided access to freshwater through the diversion of natural systems thereby greatly reducing the water entering aquatic ecosystems (rivers, streams, estuaries and the ocean) (Montagna *et al.* 2013).

According to the Millennium Ecosystem Assessment (MEA 2005) the amount of water impounded has quadrupled since 1960. Nilsson *et al.* (2005) found that over half (172 out of the 292) of large river systems globally are affected by dams. It is likely that this number has risen since 2005. Doll *et al.* (2009) estimated that total global water withdrawals was 4000 km^3/yr, which equates to approximately one tenth of renewable water resources. Of the total water withdrawal roughly a quarter is consumptive, used primarily for irrigation, that then evapotranspirates instead of returning to rivers (Doll *et al.* 2009).

The Motherwell Canal carries stormwater run-off and sometimes raw sewage into the Swartkops Estuary, Port Elizabeth

Housing developments on Thesen Island, Knysna

In some situations aquatic ecosystems receive more freshwater than they would have under natural conditions. Land use changes such as deforestation, cultivation and poorly planned urban development increase stormwater runoff. Interbasin water transfers, agricultural return flow, stormwater inflow from urban areas, overflow of septic tanks and pumping of effluent from Waste Water Treatment Works (WWTWs) can increase freshwater inflow (Lawrie *et al.* 2010, Whitfield *et al.* 2012).

Litter surrounding mangrove habitat at the uMkhomazi Estuary, KwaZulu-Natal

Subsistence fishing using illegal gill nets

Estuaries form the interface between the marine and freshwater environments and as a result are complex, dynamic and productive ecosystems. Estuaries provide numerous ecosystem services, such as regulating (erosion control), provisioning (food and water), supporting (nursery areas) and cultural services (recreation and tourism) (Costanza *et al.* 1997; Barbier *et al.* 2011, van Niekerk & Turpie 2012). Consequently, they are the most heavily utilised and threatened ecosystems worldwide. Water quality and ecological functioning of estuaries closely reflect human activity, not only along the estuarine sector itself, but also within its entire upstream catchment (Billen *et al.* 2001).

The natural variability of estuaries is primarily driven by freshwater inflow.

Changes in the water regime (quantity, quality or timing) affects the geomorphology, hydrodynamics, water quality, habitat availability, connectivity and ecological processes of estuaries. This in turn affects the composition, abundance and richness of estuarine biota. These changes compromise the ability of estuaries to provide the ecosystem services that support mankind. Climate change will further exacerbate the issue of reduced freshwater inflow as precipitation and temperature patterns will be affected (Alber 2002). Shifts in rainfall regimes will drive changes in sedimentary processes, saline conditions and nutrient supply to estuarine waters (van Niekerk *et al.* 2012). This will alter biotic zonation and availability of water for humans (Hirji & Davis 2009).

The need to ensure that aquatic ecosystems receive sufficient water to maintain adequate functioning and future persistence has only recently been realised. EWRs (previously referred to as environmental/ ecological flow assessments in South Africa) address the water regime required to maintain the functioning and health of aquatic ecosystems (King *et al.* 2005; Montagna *et al.* 2002; Yang *et al.* 2005; Arthington *et al.* 2006; Adams 2014). Since the 1980s The United States, Australia and South Africa have been leaders in advancing methodology used to determine EWRs. Historically, EWR studies focused on iconic species, often commercially important species, such as fish. There has since been an evolution from the initial simplistic hydrological determinations to integrated ecosystem based approaches that incorporate numerous biotic and abiotic components (Borja & Dauer 2008). Most methods currently in use are holistic and adaptive recognising that it is necessary to provide water for aquatic ecosystems from source to sea and for all water-dependent ecological components (Arthington *et al.* 2006; Borja & Dauer 2008; Adams 2014).

The South African coastline is characterised by three biogeographic regions namely the cool-temperate west coast, the warm-temperate southern and south-east coast, and the subtropical east coast (Turpie *et al.* 2000; Harrison 2002). These regions are primarily separated due to rainfall differences. Variations in coastal topography, fluvial and marine sediment supply have resulted in a variety of estuary types along South Africa's microtidal wave-dominated coastline (Cooper 2001). Estuaries range from permanently open tide-dominated systems to permanently open river-dominated systems, temporarily open/closed systems, estuarine lakes and estuarine bays (Whitfield 1992).

South African is a semi-arid country with a mean annual rainfall of 450 mm compared to a world average of 860 mm (King *et al.* 2005). In 2000 five of the country's 19 Water Management Areas (WMAs) were already in deficit, a situation which is likely to worsen. The climatic range across South Africa resulted in human settlements developing unevenly across the coastline. In order to meet demands water has been diverted from water rich areas such as the Orange River to supply areas in deficit. In many catchments water has been allocated to different resources and thus little reaches aquatic ecosystems. South Africa supports over 250 functional estuaries, most of which are small (<50 ha) systems. The majority (70%) of South Africa's estuaries have restricted inlets due to strong wave action and high sediment availability (van Niekerk *et al.* 2012). During periods of low freshwater inflow a sandbar develops across the mouth of the estuary preventing marine connectivity. These temporarily open/closed estuaries (TOCES) are similar to systems found in Australia and in some places in America.

Decreased freshwater inflow to aquatic ecosystems is likely to be further compounded by the effects of global climate change. Downscaled regional climate models indicate that the eastern part of South Africa will have increased incidences of summer rainfall while the western parts will experience slightly reduced winter rainfall (Hewitson & Crane 2006; Engelbrecht *et al.* 2009, 2011). The eastern parts may therefore experience increased freshwater inflow and the western parts decreased runoff. Tidal gauge measurements in South Africa have indicated an increase in sea level by approximately 1.2 mm/yr over the last three decades (South African Environmental Observation Network 2012). This trend will accelerate in the future thus resulting in increased coastal erosion, inundation of low lying land and estuaries, salt water intrusion into groundwater and raised groundwater tables.

The response of estuaries to changes in freshwater inflow

Estuaries experience three main hydrodynamic states: open, semi-closed and closed mouth condition (Snow & Taljaard 2007). The sensitivity of an estuary mouth to closure is related to the amount of river inflow, especially during low flow periods, necessary to maintain open mouth conditions. Certain physical parameters make estuaries more sensitive to flow modifications: frequency of mouth closure, size, availability of sediment, wave action in the mouth, river inflow and extent of saline intrusion (DWA 2010; Adams 2012). These parameters are mostly influenced by seasonal base flows, but flooding events are also important for the long-term equilibrium of an estuary.

Freshwater abstraction activities (dam construction and run off river abstraction for irrigation) are usually sited at permanently open estuaries that have large catchments and relatively high runoff throughout the year (Alber 2002).

Figure **1** illustrates the influence of the water regime on the functioning of estuaries and the subsequent response of estuarine biota. This conceptual model is further expanded in Figure 2 which schematically depicts the generic response of estuaries to a reduction in freshwater inflow. In South Africa, the extent of freshwater inflow reduction varies from nearly 100% (e.g. Kromme) to about 5% (e.g. Keurbooms) in permanently open estuaries. Reduced seasonal base flow or an extended duration of low flow in permanently open estuaries may cause mouth closure. Saltwater intrusion further upstream and hypersaline conditions in semi-arid areas may be experienced due to reduced flow.

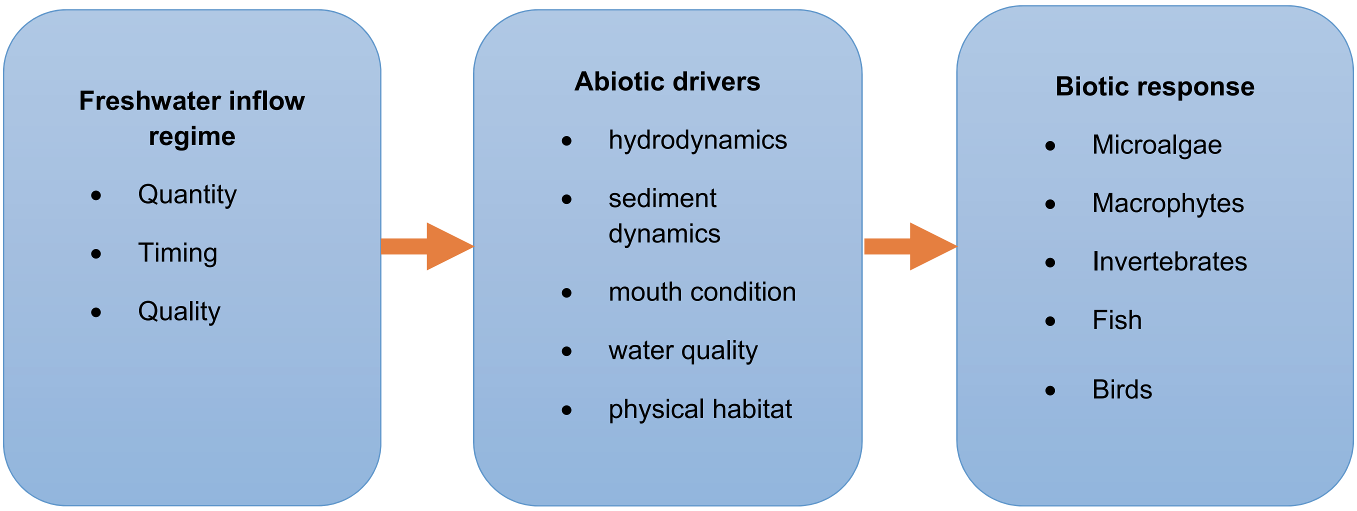


Figure 1 Conceptual model of freshwater inflow effects on estuaries.

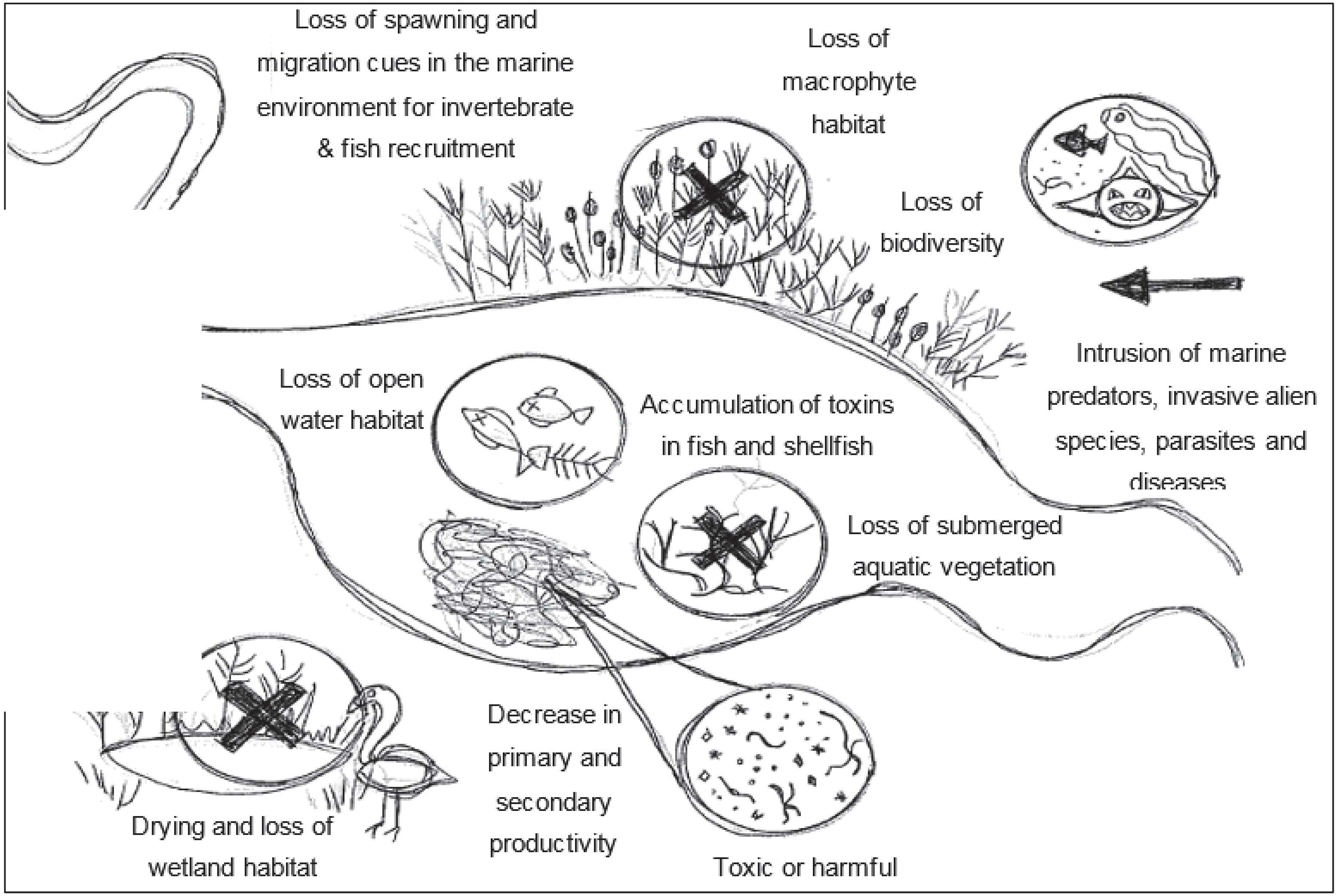


Figure 2 **Typical biotic responses of permanently open estuaries to a reduction in freshwater inflow.**

Estuaries that close to the sea (i.e. bar-built or barrier estuaries) are the most sensitive to changes in freshwater inflow (Allanson 2000; DWA 2010; Adams 2012). The bar at the mouth of these estuaries increases during periods of reduced freshwater inflow thus restricting marine water inflow. Freshwater abstraction prolongs residence time thus increasing pollutant concentration and eutrophication (Alber 2002). TOCEs are very sensitive to changes in freshwater inflow as this alters the timing and duration of mouth closure. Table 1 contrasts the typical responses of permanently open estuaries and temporarily open/closed estuaries to reduced freshwater inflow.

Table 1 Juxtaposing the generic responses of permanently open estuaries and temporarily open/closed estuaries to a reduction in freshwater inflow.

Permanently open estuaries	Temporarily open/closed estuaries
Mouth closure rarely occurs. Only during periods of no freshwater inflow for an extended period.	A sandbar develops at the mouth of the estuary as freshwater inflow is insufficient to scour sediment accumulation under tidal and wave processes. The mouth may remain closed for an extended period of time.
Maximum water levels decline due to reduced freshwater flooding, soil salinity increases, areas previously inundated during floods remain dry and do not provide habitat for water birds. Dieback of macrophyte habitats may occur.	Open water area increases due to mouth closure and an increase in water level. Dieback of intertidal macrophyte habitats occurs due to inundation. Water level can also decrease if freshwater inflow is small.
Water column salinity increases disturbing natural salinity gradients. The productive river estuary interface may be shifted further upstream.	Salinity declines under the influence of river in flow and seepage losses as estuary fills. Overwash events may introduce some saline water. Estuaries with reduced freshwater inflow can become hypersaline.
More marine species may enter the estuary as saline conditions dominate. The river plume that cues migration of estuary associated species becomes weaker. Estuarine species may be displaced by marine counterparts in extreme cases.	Estuary can become dominated by freshwater species. Species with obligate marine phases are unable to reach the marine environment.
Reduced flushing from floods can lead to the build-up of nutrients and toxic substances within the substrate. Algal blooms and eutrophic conditions may occur, especially in the upper and middle reaches where tidal flushing is weak.	Stable sheltered conditions and nutrient enrichment due to reduced flushing promote blooms of phytoplankton and macroalgae. Water quality may deteriorate due to eutrophic conditions. Anoxic conditions can result in fish kills.

The amount of water reaching the coast is affected by dams (reservoirs and impoundments), diversions and direct abstraction. The timing of water delivery is dependant not only on seasonality, but by shifts in land use that can affect runoff patterns. Water is stored in dams to provide supply to human settlements and industry during high demand periods (i.e. low rainfall periods) and is often only available during periods when dams overflow or as policy dictates to ensure

Agricultural activities on the banks of the Gamtoos Estuary, Eastern Cape

coastal ecosystems receive freshwater inflow.

Freshwater inflow regulates the salinity and nutrient concentrations as well as the physical attributes of estuaries such as inundation levels and residence time. Reduced freshwater inflow increases the influence of the tide on circulation patterns such that a stratified system with a well-developed gravitational circulation can shift to a well-mixed system where tidal exchange increases in importance. Mouth state is driven not only by freshwater inflow, but also wave energy and sediment availability. Tidal flow assists in maintaining permanently open inlets in large estuaries (>100 ha) (van Niekerk *et al.* 2012). Estuaries situated along rocky shorelines tend to remain open as sandbars cannot develop due to lack of sediment availability. The presence of headlands or reefs in the surf zone of an estuary mouth protects against wave action thereby preventing mouth closure (van Niekerk *et al.* 2012; Taljaard *et al.* 2003).

Siltation in the upper reaches of the Fafa Estuary, KwaZulu-Natal

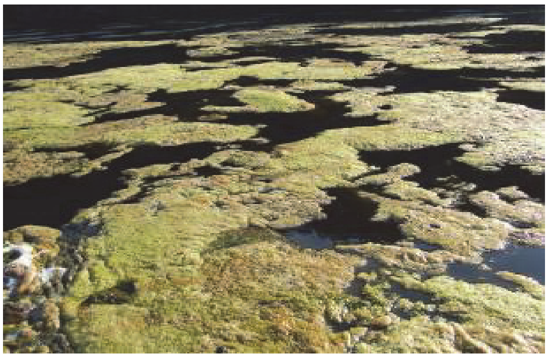
Reduced freshwater inflow coupled with high evaporation rates and low rainfall may result in hypersaline conditions. The extent and structure of the longitudinal and vertical salinity gradients of an estuary are determined by freshwater inflow. Under reduced inflow saline water extends further upstream, displacing the brackish habitat (Wortmann *et al.* 1998). This is problematic as the brackish habitat, referred to as the river estuary interface zone, is the most productive and biologically distinct part of the estuary (Bate *et al.* 2002). Loss of this mesohaline mixing zone reduces primary and secondary productivity, as well as fishery resources. The Kromme Estuary in South Africa receives almost no freshwater inflow and has essentially become an arm of the sea (Bate & Adams 2000, Snow *et al.* 2000; Strydom & Whitfield 2000; Wooldridge & Callahan 2000; Scharler & Baird 2005). Reverse salinity gradients can also development during periods of little to no inflow with the salinity at the head of the estuary exceeding that of seawater due to high rates of evaporation.

A bloom of filamentous macroalgae evident on the banks of the Gwaing Estuary, Western Cape

Increased freshwater inflow can increase the frequency of mouth breaching. The small Mhlanga Estuary situated within the eThekwini Municipality along the KwaZulu-Natal (KZN) coastline receives treated water from nearby WWTWs. Increased inflow has significantly increased the frequency of mouth breaching (Lawrie *et al.* 2010). This has resulted in an unstable system with low biotic diversity and biomass (DWAF

Cows grazing on the banks of the Sundays Estuary, Eastern Cape

2002' 2003a; Perissinotto *et al.* 2004). When the mouth closes, the accumulation of nutrients leads to eutrophication and algal blooms.



A bloom of *Cladophora glomerata* at the Great Brak Estuary, Western Cape

Freshwater inflow plays an important role in flushing accumulated toxins and metals from estuarine sediment. Retention time, i.e. the length of time materials remain in an estuary, is increased during periods of low inflow. Reduced flushing causes hypoxic conditions and the accumulation of toxins (Allanson 2000; Whitfield & Bate 2007; Adams 2012). Following dam construction and increased nutrient loads from anthropogenic inputs the Neva Estuary on the Gulf of Finland experienced increased occurrence and biomass of cyanobacterial blooms (Nikulina 2003). Similarly cyanobacterial blooms have occurred in the Sundays and Goukamma estuaries in response to surrounding agricultural inputs (Kotsedi *et al.* 2012; Kaselowski & Adams 2013).

Fish kills are often a result of eutrophic conditions

Closed estuaries tend to become eutrophic as increased nutrients cannot be assimilated (Alber 2002). Increased inflow from wastewater discharge and septic tank overflow increases mineral nutrient concentrations. Excessive nutrient input from anthropogenic sources has led to increased occurrences of eutrophication. Epiphytes, macroalgae and phytoplankton proliferate under high nutrient concentrations reducing light availability to submerged macrophytes. Invasive, nuisance and toxic species also become more abundant under eutrophic conditions which affects trophic structure (Whitfield *et al.* 2012).

As the organic plant material produced under eutrophic conditions decomposes oxygen is depleted resulting in invertebrate and fish kills. Bottom sediment may become anaerobic liberating toxins (trace metals, persistent organic pollutants, ammonia, chlorine, fluoride, cyanide, sulfides, phenols and aromatic hydrocarbons) that had been sequestered from the water column (Adams 2012). Toxins and contaminants can be harmful to aquatic organisms and ultimately to humans. Artificial breaching, whether mechanical or through releasing pulses of water from an upstream dam, is done to relieve these unfavourable conditions. Eutrophic conditions, harmful algal blooms and fish kills affect the aesthetic and recreational value of estuaries which can reduce eco-tourism opportunities.

The physical changes and reduced variability of estuaries caused by reduced freshwater inflow inherently affects the biodiversity supported. The trophic structure of estuaries is affected by changes in freshwater inflow. Numerous studies have shown how changes in freshwater inflow affect recruitment, biomass, species composition and distribution of both invertebrates and vertebrates in estuaries. Freshwater inflow supplies the nutrients required to stimulate production of phytoplankton and zooplankton and, ultimately, the larval, juvenile and adult fish that depend on them as food sources (Morgan *et al.* 2005).

Resource Directed Measures

Chapter 3 of South Africa's National Water Act (Act 38 of 1998) recognises that water is a national asset and that reserves need to be allocated to meet basic human needs and the environment, before water can be utilised by the different users. The act requires the Classification of South Africa's water resources (including estuaries), as well as the definition of Resource Quality Objectives (i.e. is to establish clear goals relating to the quality of the relevant water resources and the Reserve (i.e. the water required to protect the aquatic ecosystems of the water resource). The Act stipulates that until a system for official classification system can be developed, the Minister may make a preliminary determination of class or resource quality objectives. The so-called "Preliminary Reserve Method" involves setting a Recommended Ecological Category (i.e. desired state), recommended Ecological Reserve (i.e. flow allocation to achieve the desired state) and recommended RQOs for a resource on the basis of its present health status and its ecological importance. Once the official classification system is developed, the results from the preliminary studies will be considered and incorporated (possibly with some amendment, pending urgent social and economic considerations). The method to determine the ecological water requirements of estuaries were established soon after the promulgation of the National Water Act in 1998 (DWAF 1999, DWA 2008) and is now in its 3rd version (DWA, in press). It was developed by a core team of specialists (Taljaard *et al.* 1999, updated in 2004/8) with input from the Consortium for Estuarine Research and Management (CERM). The method follows a generic methodology, outlined in Table 2, which can be carried out at different levels of effort (e.g. rapid, intermediate or comprehensive). During the last three years progress has also been made on the development of an official desktop assessment method to assist with strategic level planning on a regional scale (applied in the Mvoti to Umzimkulu and Gouritz WMAs).

Table 2 **Generic methodology for determining the ecological water requirements of estuaries.**

Step 1	Initiate study defining the study area, project team and level of study.
Step 2	Delineate the geographical boundaries of the resource units.
Step 3a	Determine the **Present Ecological Status** (PES) of resource health (water quantity, water quality, habitat and biota) assessed in terms of the degree of similarity to the reference condition (referring to natural, unimpacted characteristics of a water resource, and must represent a stable baseline based on expert judgement in conjunction with local knowledge and historical data). An Estuarine Health Index (EHI) is used as indicated in Table 3. The estuarine health score is translated into one of six ecological classes (Table 4).
Step 3b	Determine the **Estuary Importance Score (EIS)** that takes account the size, the rarity of the estuary type within its biographical zone, habitat, biodiversity and functional importance of the estuary into account importance (Table 5 and 6). These scores (except the functional importance) already have been determined for all estuaries in South Africa as part of the NBA 2011 (Turpie *et al.* 2012, or future updates).
Step 3c	Set the **Recommended Ecological Category (REC)** which is derived from the PES and EIS (or the protection status allocated to a specific estuary). **Guidelines to assign REC based on protection status and importance, as well as PES of estuary,** are provided in Table 7. An estuary cannot be allocated an REC below a category "D". Therefore systems with a PES in categories 'E' or 'F' needs to be managed towards achieving at least a REC of "D".
Step 4	**Quantify the ecological consequences of various runoff scenarios** (including proposed operational scenarios) where the predicted future condition of the estuary is assessed under each scenario. As with the determination of the PES, the EHI is used to assess the predicted condition in terms of the degree of similarity to the reference condition.
Step 5	Quantify the (recommended) **Ecological Water Requirements** which represent the lowest flow scenario that will maintain the resource in the REC.
Step 6	Estimate (recommended) **Resource Quality Objectives (Ecological Specification)** for the recommended REC, as well as future **monitoring requirements** to improve the confidence of the EWR. The level of available historical data in combination with the level of effort expended during the assessment determines the level of confidence of the study. Criteria for the confidence limits are summarised in Table 8.

Table 3 Calculating estuary health using the Estuarine Health Index.

VARIABLE	SCORE	WEIGHT	WEIGHTED SCORE
Hydrology	…	25	…
Hydrodynamics and mouth condition	…	25	…
Water quality	…	25	…
Physical habitat alteration	…	25	…
Habitat health score			**…**
Microalgae	…	20	…
Macrophytes	…	20	…
Invertebrates	…	20	…
Fish	…	20	…
Birds	…	20	…
Biotic health score			**…**
ESTUARY HEALTH SCORE Mean (Habitat health, Biological health)			**…**

Table 4 **The six ecological classes for indicating the Present Ecological Status of an estuary.**

EHI SCORE	PES	GENERAL DESCRIPTION
91-100	A	Unmodified, or approximates natural condition; the natural abiotic template should not be modified. The characteristics of the resource should be determined by unmodified natural disturbance regimes. There should be no human induced risks to the abiotic and biotic maintenance of the resource. The supply capacity of the resource will not be used
76-90	B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place, but the ecosystem functions are essentially unchanged. Only a small risk of modifying the natural abiotic template and exceeding the resource base should not be allowed. Although the risk to the well-being and survival of especially intolerant biota (depending on the nature of the disturbance) at a very limited number of localities may be slightly higher than expected under natural conditions, the resilience and adaptability of biota must not be compromised. The impact of acute disturbances must be totally mitigated by the presence of sufficient refuge areas.
61-75	C	Moderately modified. A loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged. A moderate risk of modifying the abiotic template and exceeding the resource base may be allowed. Risks to the wellbeing and survival of intolerant biota (depending on the nature of the disturbance) may generally be increased with some reduction of resilience and adaptability at a small number of localities. However, the impact of local and acute disturbances must at least partly be mitigated by the presence of sufficient refuge areas.
41-60	D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred. Large risk of modifying the abiotic template and exceeding the resource base may be allowed. Risk to the well-being and survival of intolerant biota depending on (the nature of the disturbance) may be allowed to generally increase substantially with resulting low abundances and frequency of occurrence, and a reduction of resilience and adaptability at a large number of localities. However, the associated increase in the abundance of tolerant species must not be allowed to assume pest proportions. The impact of local and acute disturbances must at least to some extent be mitigated by refuge areas.
21-40	E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.
0-20	F	Critically modified. Modifications have reached a critical level and the lotic system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

Table 5 **Determining the Estuary Importance Score.**

CRITERION	SCORE	WEIGHT	WEIGHTED SCORE
Estuary Size	…	15	…
Zonal Rarity Type	…	10	…
Habitat Diversity	…	25	…
Biodiversity Importance	…	25	…
Functional Importance	…	25	…
Weighted Estuary Importance Score			**…**

Table 6 **The Estuarine Importance rating system.**

EIS	IMPORTANCE RATING
81-100	Highly important
61-80	Important
0-60	Of low to average importance

Table 7 **Guidelines for assigning the Recommended Ecological Category based on protection status and importance, as well as Present Ecological Status of an estuary.**

PROTECTION STATUS AND IMPORTANCE	REC	POLICY BASIS
Protected area	A or BAS*	Protected and desired protected areas should be restored to and maintained in the best possible state of health
Desired Protected Area (based on complementarity)		
Highly important	PES + 1, min B	Highly important estuaries should be in an A or B category
Important	PES + 1, min C	Important estuaries should be in an A, B or C category
Of low to average importance	PES, min D	The remaining estuaries can be allowed to remain in a D category

* BAS = Best Attainable State

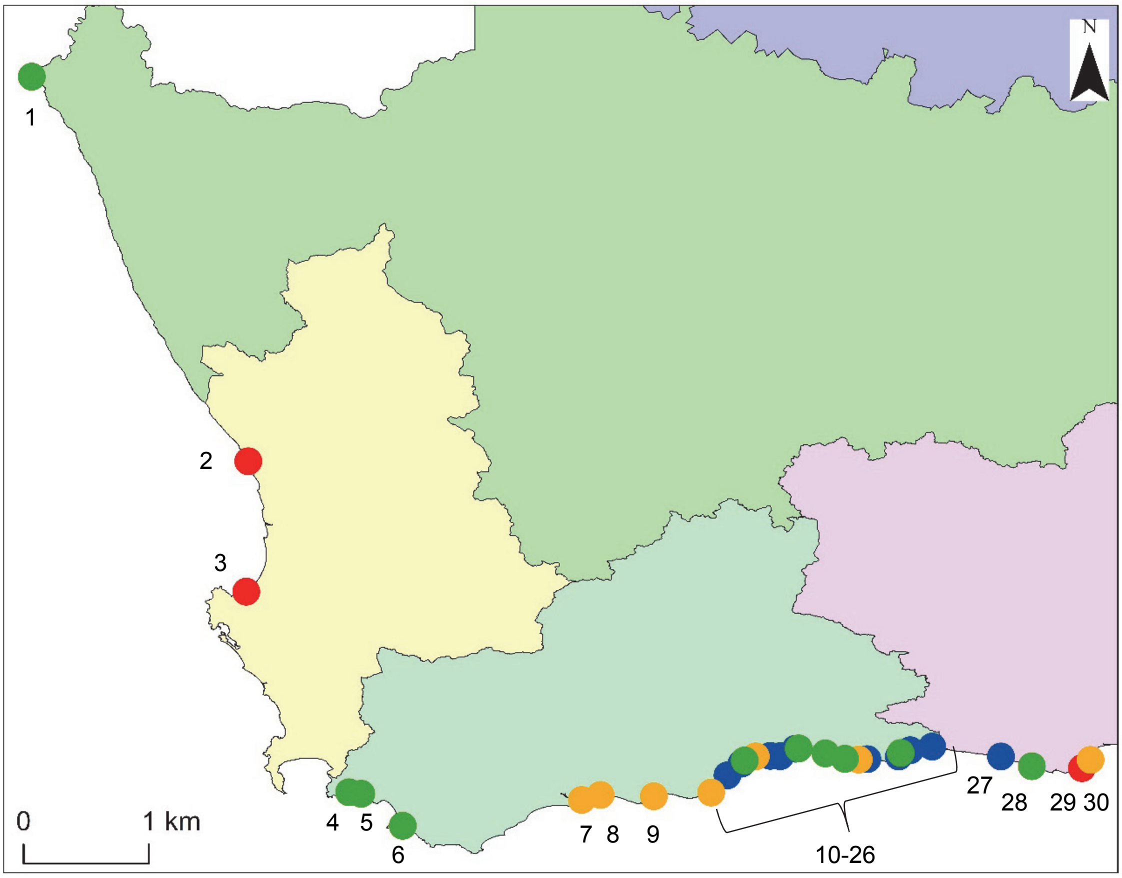
Table 8 **Criteria for confidence levels.**

CONFIDENCE LEVEL	SITUATION	EXPRESSED AS PERCENTAGE
Very Low	No data available for the estuary or similar estuaries	(i.e. < 40% certain)
Low	Limited data available	40-60% certainty
Medium	Reasonable data available	60-80% certainty
High	Good data available	> 80% certainty

The Water Research Commission funded a number of multi-institutional, multi-disciplinary research studies that contributed to the improvement of EWR studies and methods over the years. This was done through CERM, which was a group of interested people collaborating on the wise management of estuaries. Workshops were held over the years to identify research projects where CERM members could co-operate. Initially a Cape estuary group worked closely together on both research and DWAF EWR studies which led to considerable progress in understanding and managing the water requirements of estuaries. The effects of a dam release into the Kromme Estuary (Bate & Adams 2000), the importance of the river estuary interface zone in the Gamtoos Estuary (Bate *et al.* 2002; Whitfield & Wood 2003) and the ecological water requirements of the East Kleinemonde Estuary (Whitfield *et al.* 2008; van Niekerk *et al.* 2008) were some of the projects. Many post-graduate students were involved with this research. In a Water Research Commission project, "Contributions to Information Requirements for the Implementation of Resource Directed Measures for Estuaries" capacity was extended to KZN through joint research and specific EWR studies on the uMdloti and Mhlanga estuaries. Other important Water Research Commission reports were "Development of resource monitoring procedures for estuaries" (WRC K5/158/0/1) and "Evaluation of ecological flow requirements of South Africa's estuaries – hydrodynamic perspective "(KV302/12). Now days completed EWR studies are a valuable collation of available information on an estuary. These studies have formed the backbone of the development of Estuary Management Plans (EMP) as they provide a detailed understanding of the structure and function of an estuary. The quality of the EMP is directly linked to the availability of data from an EWR study.

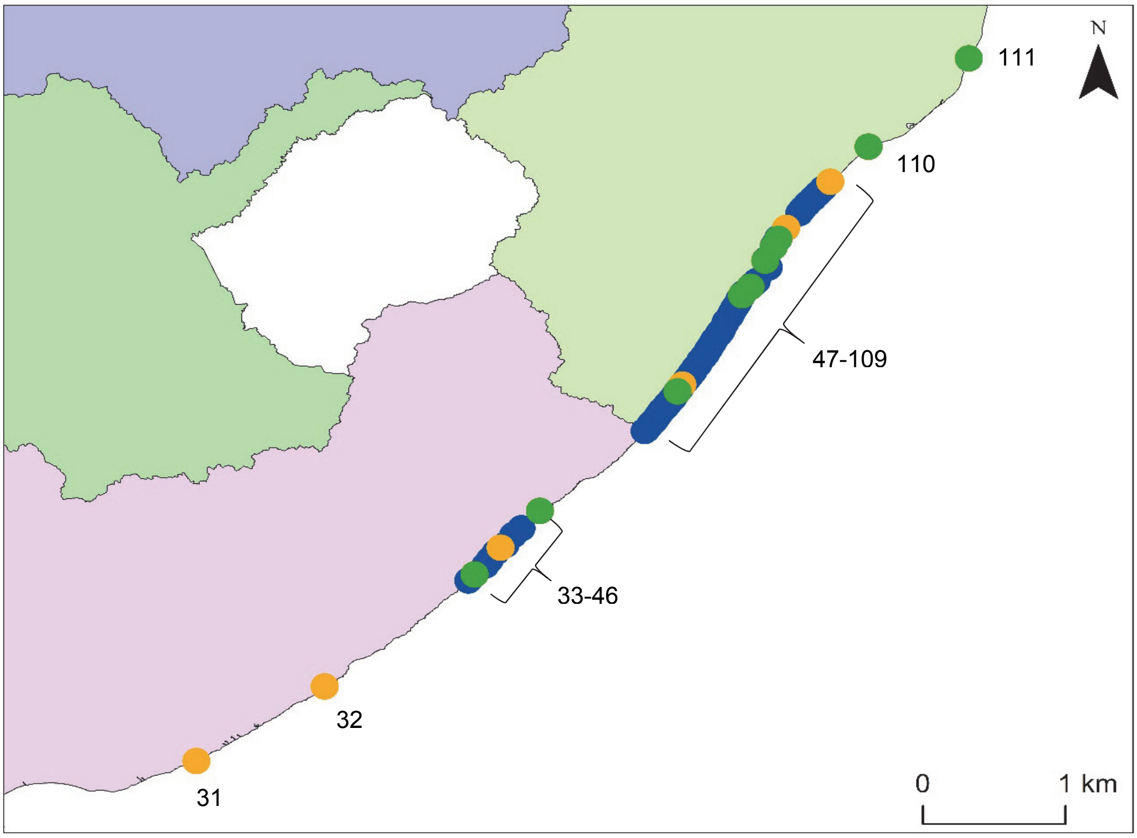
Completed ecological water requirement studies for South African estuaries

Completed EWR reports for estuaries were obtained from DWS, the CSIR and other consultants and scientists. Data pertaining to the health assessment and EWR studies were extracted from reports and summarised in tables to allow for an overall assessment. Studies that contributed to the development of the RDM method or advanced understanding of estuary responses to freshwater inflow were identified and described. EWR studies have been completed for 39% of South Africa's estuaries since commencement in 1999. Figure 3 and 4 depict the distribution of estuaries across the South African coastline for which EWRs have been determined. Table 9 to Table 13 and Figure 5 summarise all EWR studies completed to date. If studies have been reassessed, the most recent study was provided. A comparison of revised scores is provided in Table 14. Initially studies were completed for individual estuaries or as part of catchment studies that assessed the EFR of rivers and estuaries. There has now been a move to managing estuaries at the scale of a WMA. There are also ongoing Preliminary EWR studies of the Usutu to Mhlathuze WMA (Matikulu and Mlalazi estuaries). Estuaries within the eThekwini Municipality are in the process of being reassessed as ecological scenarios were not considered in the 2013 classification. In this report estuaries are assessed from the west to east coast, firstly assessing individual studies followed by catchment and WMA studies.



1. Orange 2. Olifants 3. Berg 4. Palmiet 5. Bot 6. Uilkraals 7. Breede 8. Duiwenhoks 9. Goukou 10. Gouritz	11. Blinde 12. Hartenbos 13. Klein Brak 14. Great Brak 15. Maalgate 16. Gwaing 17. Kaaimans 18. Wilderness 19. Swartvlei 20. Goukamma	21. Knysna 22. Noetsie 23. Piesang 24. Matjies 25. Bloukrans 26. Groot 27. Tsitsikamma 28. Kromme 29. Seekoei 30. Sundays

Figure 3 **Ecological water requirement studies completed for estuaries on the west and south coast of South Africa (blue indicating desktop assessments, green: rapid, yellow: intermediate and red: comprehensive).**



31. East Kleinemonde	59. Uvuzana	86. Mzimayi
32. Great Fish	60. Kongweni	87. Mpambanyoni
33. Nahoon	61. Vungu	88. Mahlongwa
34. Mbanyana	62. Mhlangeni	89. Mahlongwane
35. Ntlonyane	63. Zotsha	90. uMkhomazi
36. Xora	64. Boboyi	91. Ngane
37. Mncwasa	65. Mbango	92. Umgababa
38. Mpako	66. Umzimkulu	93. Msimbazi
39. Nenga	67. uMthente	94. Lovu
40. Mnenu	68. Mhlangamkulu	95. Little Manzimtoti
41. Mngazi	69. Damba	96. Manzimtoti
42. Mtata	70. Koshwana	97. Mbokodweni
43. Mdumbi	71. Intshambili	98. Sipingo
44. Mtakatye	72. Mzumbe	99. Durban Bay
45. Mngazana	73. Mhlungwa	100. uMngeni
46. Mzimvubu	74. Mhlabatshane	101. Mhlanga
47. Mtamvuna	75. Mfazazana	102. uMdloti
48. Zolwane	76. Kwa-Makosi	103. Uthongathi
49. Sandlundlu	77. Mnamfu	104. Mhlali
50. Ku-boboyi	78. Mtwalume	105. Bob's stream
51. Tongazi	79. Mvuzi	106. Seteni
52. Kandandhlovu	80. Fafa	107. Mvoti
53. Mpenjati	81. Mdesingane	108. Mdlotane
54. Umhlangankulu	82. Sezela	109. Nonoti
55. Kaba	83. Mkumbane	110. Zinkwasi
56. Mbizana	84. uMuziwezinto	111. Thukela
57. Mvutshini	85. Nkomba	112. Siyaya
58. Bilanhlolo		113. St Lucia

Figure 4 **Ecological water requirement studies completed for estuaries on the east coast of South Africa (blue indicating desktop assessments, green: rapid, yellow: intermediate and red: comprehensive).**

Considering that the majority of South Africa's estuaries are TOCEs, it is logical that 71% of estuaries assessed were TOCEs. EWR, in varying levels of confidence, have been determined for 38% of South Africa's TOCEs. Half of the country's permanently open estuaries and estuarine bays have been assessed. However Durban Bay was only a desktop assessment as part of the classification for the Mvoti-Umzimkulu WMA. The EWR of more estuarine lakes and river mouths should be assessed as only 25 and 36%, respectively, have been determined.

Due to lack of long-term monitoring data, time and budgetary constraints most (69%) ecological water requirement studies were completed as desktop assessments. Equal numbers (14%) of rapid and intermediate EWR studies have been completed. Comprehensive reserve determinations have thus far been restricted to large permanently open systems as these catchments have a greater mean annual run-off and are therefore targeted for water abstraction schemes. The classification of the Mvoti-Umzimkulu WMA assessed 22% of South Africa's estuaries. The Gouritz WMA study assessed 7% of the country's estuaries and the Mtata catchment study assessed 4% of the 291 estuaries (van Niekerk *et al.* 2013).

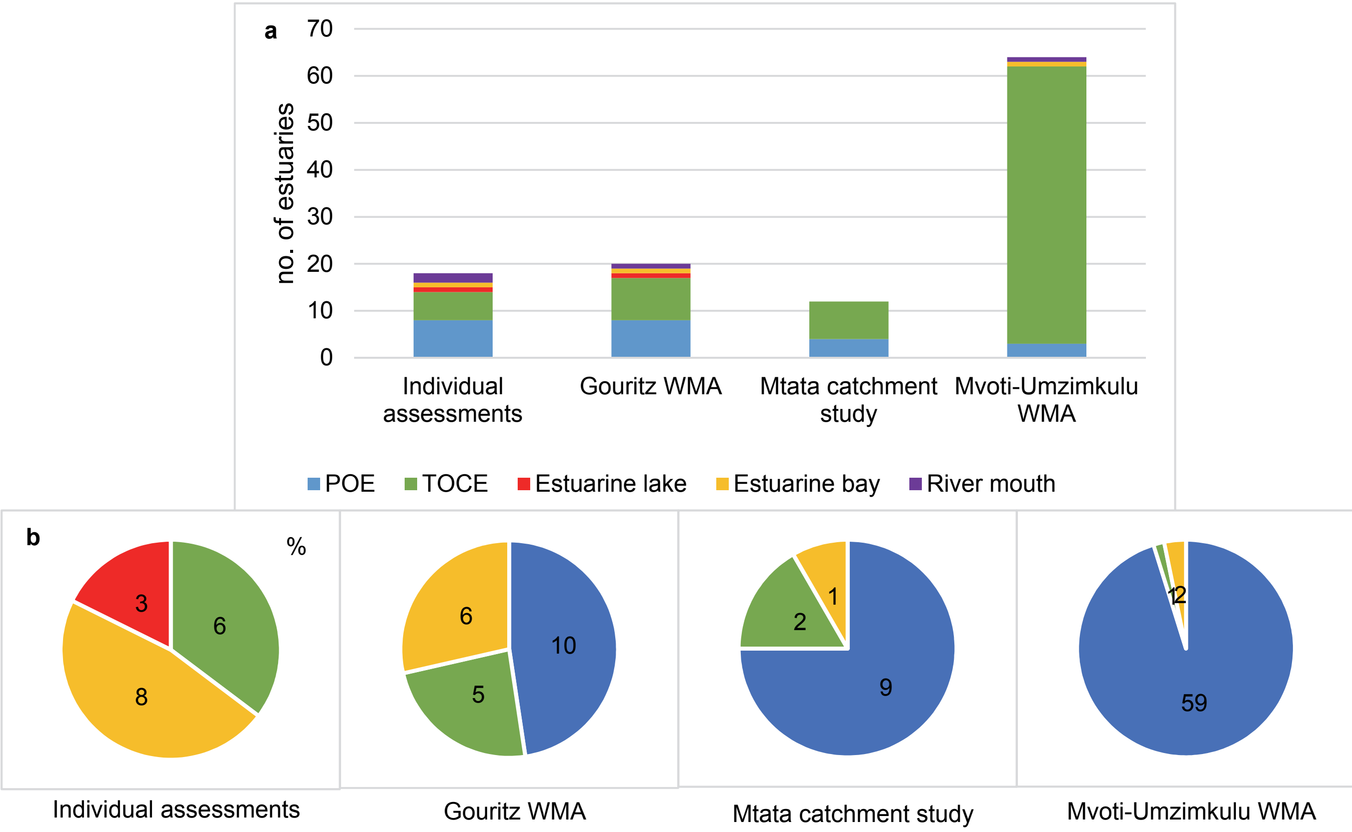


Figure 5 **Summary of completed ecological water requirement studies for South African estuaries (a) representing the number of different estuary types studied per catchment or water management area and (b) representing the level at which determinations were undertaken (blue: desktop, green: rapid, yellow: intermediate and red: comprehensive).**

Studies were usually commissioned by the DWS specifically for the issuing of new water use license applications. Some studies were undertaken for other purposes such as the uMdloti and Mhlanga estuaries were assessed as the eThekwini Metropolitan planned to release treated sewerage water into the systems (DWAF 2002). The EWR study for the Siyaya Estuary in KZN was paid for by Richards Bay Minerals (DWAF 2006). The East Kleinemonde EWR study was a component of a Water Research Commission project on water requirements of temporarily open / closed estuaries (Whitfield *et al.* 2008). The Keurbooms study was funded by the Plettenberg Bay Municipality (Bitou Municipality South Africa 2008).

The Outeniqua catchment study of 2009 assessed nine estuaries along the south coast. The nearby Sout and Matjies estuaries were assessed in 2007 as part of the K70a Quaternary catchment study for an Environmental Impact Assessment. The Tsitsikamma Estuary study included preliminary assessments of other estuaries in the K80 tertiary catchment, which were not assessed due to budgetary constraints. The Gouritz WMA 16 (which under the new classification by the National Water Resource Strategy falls into the Breede-Gouritz WMA 8) study completed in 2015 determined the EWR of 10 estuaries, while the scores from these previous studies were kept for the other estuaries within the WMA.

The lower reaches of the Goukamma Estuary, Western Cape

The Mtata River Basin study assessed the health of 14 estuaries in the former Transkei region, eight of which were desktop assessments. Low confidence desktop assessments were based on available information and thus should not be used to inform water use licenses (DWAF 2000). A classification of the 64 estuaries within the Mvoti-Umzimkulu WMA was first published in 2013 and revised in 2015. Some estuaries located within the eThekwini Metropolitan had previously been assessed (Zotsha, Umzimkulu, Little aManzimtoti, Mbokodweni, uMngeni, Mhlanga, uMdloti and uThongathi). The Mvoti-Umzimkulu WMA study was the application of a regional scaled method for the Eco classification of estuaries. The ecoclassification of estuaries was first described in a Water Research Commission project (K5/21872012). This method uses available data sets and expert assessments. This was tested in the official DWS Water Resource Classification process for the Mvoti to Umzimkulu WMA. This is the proposed method for assessing ecological status to be used in the next National Biodiversity Assessment of estuaries (2018 NBA).

Table 9 **Ecological water requirement studies for South African estuaries completed as part of larger scale catchment studies.**

Year implemented	Larger scale assessment	Estuaries assessed
2000	Mtata River Basin Study	Mbanyana, Ntlonyane, Xora, Mncwasa, Mpako, Nenga, Mnenu, Mngazi, Mtata, Mdumbi, Mtakatye and Mngazana
2001	Amatole Water Resources System	Nahoon
2001	Mhlathuze System Ecological Reserve study	Mhlathuze and Nhlabane
2002	Breede River Basin study	Breede
2003	K80 Tertiary Catchment study	Tsitsikamma Preliminary assessments on: Bloukrans, Witels (Coldstream), Lottering, Elandsbos, Geelhoutbos, Kleinbos, 'Waterfall' at Grootpunt, Storms, Bruglaagte, Sanddrif, Elands, Jaftakraal, Groot (Oos), Eerste, Klipdrif (Wes), Boskloof, Stream at Grootpunt, Kaapsedrif, Klipdrif (Oos) and Slang
2004	Thukela Water Project	Thukela
2007	Southern Cape K70a Quaternary Catchment	Matjies and Sout
2007	Kromme/Seekoei Catchments Reserve Determination Study	Kromme and Seekoei
2009	Outeniqua Catchment Ecological Water Requirements Study	Great Brak, Maalgate, Gwaing, Kaaimans, Swartvlei, Goukamma and Noetsie
2010	Western Cape Water System Supply Study	Berg
2011	eThekwini Municipality Water Reuse and Recycling Project	Little aManzimtoti, Mbokodweni and uMngeni.
2011	Mzimkhulu river catchment water resource study	Umzimkulu

Individual assessments

The Orange Estuary, situated between the towns of Alexander Bay in South Africa and Oranjemund in Namibia, had the lowest PES (Category D) along this coast. Elevated baseflows (return flow, agricultural and hydroelectrically power releases) prevent mouth closure and related back-flooding of intertidal and supratidal habitat (DWAF 2003, 2012). This impact is amplified by a causeway that cuts off the floodplain from the main water body, resulting in desertification of the extensive salt marshes that provide a critical habitat for birds along this coast. The Olifants Estuary on the southern boundary of Namaqualand was assessed at a comprehensive level for water allocation purposes. Two major dams (Clanwilliam and Bulshoek) threaten the open mouth status of this estuary (DWAF 2006b). Salinity creep and degradation of water quality resulted in macrophyte encroachment and algal blooms (eutrophication) in the upper and middle reaches of this estuary during the low flow period, putting the higher trophic levels under significant stress in summer. Over fishing (gill nets) had a significant impact on the fish condition.

A similar situation is evident at the Breede Estuary also in the Western Cape (DWAF 2003), with most of the impact on flow and water quality. The 2003 intermediate EWR of the Breede Estuary, of which the Breede River is the largest in the Western Cape, determined that at least 50% of the natural mean annual runoff (MAR) is required to ensure the adequate functioning of the estuary. Water resources in the stressed Breede Catchment need to be properly managed to ensure the health of the surrounding water resources. Invasive alien plants are rife in the riparian habitats of downstream estuaries which reduce natural diversity and utilises more water resources than indigenous vegetation. The Uilkraals Estuary situated near Cape Agulhas indicated that the shift from a permanently open system to one that closes for long periods was due to dam development (Anchor Environmental Consultants 2012). According to the permit for the Kraaibosch Dam, located 10 km upstream from the Uilkraals Estuary, only winter inflow is allowed to be retained and summer flow must be released. It is, however, anticipated that there will be a 40% increase in summer allocations out of the Kraaibosch Dam as a result of increasing demand from agriculture.

Although the MAR to the Tsitsikamma Estuary has been reduced by 33% from reference conditions, it was still in a healthy state. However the specialists on the rapid reserve determination study described a future negative trajectory of change (DWAF 2004). This study was completed in 2003 after dams were proposed in the upper reaches and prior to this study there was no quantitative understanding of the effects of reduced freshwater inflow on the system. It was predicted that once the dams were built the physical habitat of the Tsitsikamma Estuary would decline resulting in B PES (DWAF 2004).

The Kromme and Seekoei estuaries near St Francis in the Eastern Cape were assessed together in 2006. In the Kromme Estuary the MAR is equivalent to the MAR of the dams (Churchill and Impofu) in the catchment, the estuary receives no freshwater inflow and has become a side arm of the sea (DWAF 2005). Although the estuary is a desired protected area, it is unlikely that the PES could be improved to anything better than a Category C. The poor habitat and biotic score of the Seekoei Estuary was attributed to changes in river inflow, the construction of a causeway across the estuary and artificial breaching causing more frequent mouth closure (DWAF 2006). Biota in the estuary have taken strain during drought years and hypersaline conditions with almost 40% of the original plant species lost from the system (Adams *et al.* 1992).

The Sundays and Great Fish estuaries receive enhanced freshwater inputs from an interbasin transfer scheme bringing water from the Orange River (Adams 2008; van Niekerk *et al.* 2013). This water is nutrient rich agricultural return flow that reduces water quaility due to eutrophication. Dense phytoplankton blooms and invasive aquatic species such as waterfern have been recorded at Sundays Estuary (Adams 2008). Overexploitation of resources, particularly fish, needs to be controlled in most of these estuaries. This requires co-operative governance and interaction with the Department of Agriculture, Forestry and Fisheries. Reductions in major floods and sedimentation threaten the open mouth states of the Nahoon Estuary. Situated near East London the Nahoon Estuary is used extensively for recreational boating (DWAF 2001).

Mechanical breaching of a sandberm

The mouth of the Umzimkulu Estuary, on the subtropical KZN coast, has historically closed (Forbes *et al.* 2011). It is suspected that the frequency of mouth closure has increased, however there is a lack of records to back this. Sand mining activities and bridge construction that removed benthic habitat have attributed to the estuary's present ecological state. The Thukela river mouth experiences poor water quality due to discharge (paper, pulp and effluent) from the industrial area of Mandini (DWAF 2004b). The highly important St Lucia Estuary had the lowest (Category D) Present Ecological Status of the estuarine lakes assessed. Aside from a reduction in flow anthropogenic developments such as the drainage and canalisation of the Umfolozi swamps, the construction of weirs and an overall reduction in bird habitat on a national and international scale have contributed to its poor health (DWAF 2004a).

Charter's Creek, St Lucia Estuary, KwaZulu-Natal

Table 10 Individual ecological water requirement studies for South African estuaries grouped into their water management area from the west to east coast.

Estuary	% of natural MAR received	EHI score	PES	Importance score	REC	Estuary type	Level of study	Year completed
Orange	40	51	D	99	A or BAS	River mouth	EFR	2013
Olifants	67	70	C	99	B	POE	Comprehensive	2006
Berg	/	64	C	99		POE	Comprehensive	2010
Bot	/	71	C	94	B	TOCE	Rapid	2009
Palmiet	/	67	C	62.8		TOCE	Rapid	2009
Uilkraals	74	49	D	74	BAS	POE	Rapid/intermediate	2012
Breede	58	78	B	86	A/B	POE	Intermediate	2002
Knysna	82	78	B	100	A	Estuarine bay	Intermediate	2009
Kromme	/	49	D	66	C/D	POE	Comprehensive	2007
Sundays	95	67	C	81	B	POE	Intermediate	2008
Great Fish	90	71	C	92	B/C	POE	Rapid	2013
Nahoon	64	67	C	64	B	POE	Intermediate	2001
Tsitsikamma	67	92	A	33	A	TOCE	Rapid	2003
Seekoei	56	42	D	71	B	TOCE	Intermediate	2007
East Kleinemonde	96	87	B	70	A	TOCE	Intermediate	2008
Siyaya	71	37	E	55	B	TOCE	Rapid	2006
St Lucia	86	46	D	92	A	Estuarine lake	Rapid	2004
Thukela	73	70	C	76	B	River mouth	Intermediate	2004

Gouritz Water Management Area

Only 9% of the estuaries within the Gouritz WMA were in excellent health (Category A) and 9% were also in a poor state (Category D or E). When analysed according to 'estuarine area' rather than the number of estuaries, 79% was in good condition (Category B or B/C). Large estuarine lakes dominate this WMA from a habitat perspective. The smaller estuaries were in good health as they experience fewer pressures; however, these systems may not be as resilient to change as larger estuaries because they tend to have a higher residence time due to limited tidal exchange. Hartenbos and Piesang estuaries, for example are in poor conditions due to their urban locations. Although there is intense development around Knysna Estuary, because it functions as a bay, the health of the system remains intact and the system has a high PES (Category B) (DWA 2009b, c).

Base flow, especially during low flow periods need to be restored for about 35% of the estuaries within the Gouritz WMA. Dams have significantly reduced freshwater inflow to the Klein Brak and Great Brak estuaries (DWS 2015). Specialists described the Klein Brak Estuary as being on a negative trajectory of change due to extremely low base flows under the present state (< 1 m^3/s); particularly during the summer months.The Great Brak Estuary has been greatly impacted (PES = D) by the Wolwedans Dam, with a capacity of 23 x 10^6 m^3, located upstream. High nutrient input, overexploitation of living resources and extended periods of mouth closure are some of the major pressures affecting the natural functioning of the system (DWA 2009a). This study also showed that while dam releases could mimic an extended natural mouth regime pattern, it could not flush out organic matter leading to a decline in water quality even under open mouth conditions. Water quality needs to be improved for 52% of the estuaries particularly the Hartenbos and Piesang as has already been mentioned.

Examples of macroalgal blooms in South African estuaries

The good PES of the Sout (Category A), Swartvlei (Category B) and Wilderness estuaries is attributed to their protected status within national parks. Although the Swartvlei Estuary has been protected by SanParks since 1986 (Russell *et al.* 2012) the estuary is artificially breached to prevent the flooding of low lying housing developments (DWA 2009b). A similar situation is experienced at the Wilderness Estuary, which is also situated within the Garden

N2 bridge across the Kaaimans Estuary, Western Cape

Route National Park (DWS 2015). The Maalgate, Noetzie, Goukamma and Matjies occur in relatively remote areas in the Western Cape. Although the Keurbooms Estuary is developed in the lower reaches the upper reaches occur in an undisturbed area and freshwater inflow is largely natural (Bitou Municipality 2008).

The Goukamma Estuary falls within the Goukamma Marine Protected Areas and thus should be improved to an 'A' ecological category (DWA 2009b). The estuary still receives over 80% of its natural MAR and inexpensive adjustments such as the removal of structures in the intertidal area and improvement of water quality could reverse the negative impacts on Goukamma Estuary (Kaselowski & Adams 2013). Using available data the rapid EWR study described the water quality of the Goukamma Estuary as good (86) (DWA 2009b). It was alluded to, however, that agricultural activities in the catchment may have introduced elevated nutrients, particularly Dissolved Inorganic Nitrogen. This was confirmed by Kaselowski and Adams (2013) who discovered indications of eutrophication such as low dissolved oxygen concentrations, high microalgal biomass and frequent blooms of blue green algae in the estuary.

Duiwenhoks Estuary, Western Cape

Gwaing Estuary, Western Cape

Table 11 **Summary of completed studies for estuaries of the Gouritz Water Management Area. ([1]estuaries assessed as part of the Outeniqua catchment assessment, and [2] estuaries assessed as part of the K70a Quaternary catchment assessment.)**

Estuary	% of natural MAR received	EHI score	PES	Importance score	REMC	Estuary type	Level of study	Year completed
Duiwenhoks	82	72	C	84	B	POE	Intermediate	2015
Goukou	79	69	C	83	B	POE	Intermediate	2015
Gouritz	60	61	C/D	78	B	POE	Intermediate	2015
Blinde	70	73	B/C	27	B/C	POE	Desktop	2015
Hartenbos	61	51	D	66	C	POE	Desktop	2015
Klein Brak	76	64	C	58	C	POE	Rapid	2015
Great Brak[1]	44	58	D	72	C	TOCE	Intermediate	2009
Maalgate[1]	60	80	B	37.9	B	TOCE	Desktop	2009
Gwaing[1]	75	70	C	10.4	C	TOCE	Desktop	2009
Kaaimans[1]	75	83	B	27.9	B	POE	Desktop	2009
Wilderness	85	Lakes 75 Touw 68	B/C	85	B	Estuarine lake	Rapid	2015
Swartvlei[1]	69	78	B	87	A	Estuarine lake	Rapid	2009
Goukamma[1]	85	88	B	57	A	TOCE	Rapid	2008
Knysna[1]	82	78	B	100	A	Estuarine bay	Intermediate	2009
Noetsie[1]	90	81	B	28.3	A	TOCE	Desktop	2009
Piesang	66	51	D	71	B/C	TOCE	Desktop	2015
Keurbooms	92.7	88	A/B		A/B	POE	Desktop	2015
Matjies[2]	84	89	B	26	A	TOCE	Rapid	2007
Sout[2]	90	95	A	40	A	POE	Intermediate	2007
Groot	87	86	A	62	B	TOCE	Desktop	2015
Bloukrans	98	96	A	51	B	River mouth	Desktop	2015

Mtata catchment study

Flow patterns in the permanently open Mtata Estuary have been reversed as a result of a hydroelectric scheme in the catchment (DWAF 2000; Adams *et al.* 2002). The estuary now receives higher flow in winter compared to summer. Estuaries in rural locations such as Xora, Mngazi and Zotsha are currently in good condition as they are mainly affected by human disturbance such as trampling, bait collecting and cattle grazing (DWAF 2000). Table 12 provides a summary of the scores obtained from the Mtata catchment RDM studies.

Table 12 Summary of completed ecological water requirement studies for estuaries of the Mtata Catchment completed in 2000.

Estuary	% of natural MAR	EHI score	PES	Importance score	Type	REMC	Level of study
Mbanyana			A		TOCE	A	Desktop
Ntlonyane			B	55.5	TOCE	B	Desktop
Xora	90	87.5	B	79.6	TOCE	A	Rapid
Mncwasa			C		TOCE	C	Desktop
Mpako			B		TOCE	B	Desktop
Nenga			B		TOCE	B	Desktop
Mnenu			A		TOCE	A	Desktop
Mngazi	90	84.8	B	45	TOCE	B	Rapid
Mtata	92	58.8	D	78	POE	C	Intermediate
Mdumbi			B	67	POE	A	Desktop
Mtakatye			A	68	POE	A	Desktop
Mngazana			B	84	POE	A	Desktop

Mvoti-Umzimkulu Water Management Area

Estuaries situated in urban areas tend to experience greater flow-related and other anthropogenic pressures. The estuaries surrounding the large metropolitan of Durban, KZN on the subtropical east coast of South Africa are testimony to this with most systems in a largely degraded to highly modified state (Little aManzimtoti, Mbokodweni, uMngeni, uMdloti, uThongathi and Siyaya). Although KZN is a water endowed area, water deficits are becoming an increasing issue, particularly in context of Durban's municipality (eThekwini) Integrated Development Plans (DWAF 2007). Currently water is transferred between the different catchments to supply the water requirements of Durban and Pietermaritzburg. Major developments have been planned for the area thus requiring the construction of new dams and improvement of the sewage systems.

The small estuaries of KZN historically have high river inflow due to the steep coastal topography. However, anthropogenic influence (e.g. sugar cane farming) has exacerbated natural rates of sedimentation as well as resulted in water quality (Mhlanga and uMdloti) and habitat loss issues (Siyaya) (DWAF 2007). In some estuaries inflow has been increased by more than double the MAR due to input from WWTW. For example the Mhlanga Estuary receives 158% of its MAR (DWAF 2000; DWA 2011; DWA 2013). The study has shown that small estuaries have very little assimilative capacity and low resilience to deal with pollution. During the closed phase, decomposition of the high organic load (eutrophication or organics in waste water) into these small systems frequently causes oxygen stress, and in extreme cases fish kills.

Water hyacinth, *Eichhornia crassipes*, and water lettuce, *Pistia stratiotes*, choke the lower reaches of the Little Amanzimtoti Estuary, KwaZulu-Natal

Table 13 Summary of completed studies for estuaries of the Mvoti to Umzimkulu Water Management Area. (* POE, ** Estuarine bay, *** River mouth)

Estuary	% natural MAR	PES	Importance score	REC	Estuary	% natural MAR	PES	Importance score	REC	Estuary	% natural MAR	PES	Importance score	REC
Mtamvuna	87	B	66.3	A/B	Damba	84	D	37.8	C	uMkhomazi*	86	C	72.9	B
Zolwane	106	B	16.1	B	Koshwana	95	C/D	31.1	B	Ngane	88	C	31.8	C
Sandlundlu	99	C	36.9	C	Intshambili	75	C	35.5	B	Umgababa	91	C	51.8	B
Ku-boboyi	99	B	19.4	B	Mzumbe	92	C/D	46.9	C	Msimbazi	97	B	54.6	A
Tongazi	96	B/C	38.3	B/C	Mhlabatshane	100	B/C	38.1	A/B	Lovu	69	C/D	56.5	B/C
Kandandhlovu	95	B	22.6	B	Mhlungwa	98	C	35.9	C	Little Manzimtoti	133	E	34.4	D
Mpenjati	99	B/C	47.9	B	Mfazazana	93	C	43.4	B	Manzimtoti	73	D/E	51.5	D
Umhlangankulu	100	C	49.4	C	Kwa-Makosi	94	B/C	41.4	B	Mbokodweni	30	E	41	D
Kaba	97	C	25.3	C	Mnamfu	94	C	27.5	C	Sipingo*	10	F	53.9	D
Mbizana	97	B	54.5	B	Mtwalume	74	C	53.5	C	Durban Bay**	25	E	92.1	D
Mvutshini	98	B/C	12.5	B/C	Mvuzi	94	C	24.9	C	uMngeni	39	E/D	73.1	D/E
Bilanhlolo	99	C	43.1	C	Fafa	81	C/D	64.8	C/D	Mhlanga	33	D	70.3	B
Uvuzana	100	C	15.8	C	Mdesingane	100	D	19.9	D	uMdloti	84	D	72.8	C
Kongweni	48	D/E	27.1	D	Sezela	94	C	48.6	C	uThongathi	99	D	62.6	C
Vungu	96	B	22.3	B	Mkumbane	93	C	27.6	C	Mhlali	96	C/D	67.5	B/C
Mhlangeni	97	C	33.8	C	uMuziwezinto	87	C/D	49	C/D	Bob's Stream		B/C		B/C
Zotsha	97	B/C	46.9	B	Nkomba		B/C		B/C	Seteni	100	B/C	34.4	B
Boboyi	97	B	26.4	B	Mzimayi	80	C/D	21.1	C/D	Mvoti***	75	D	68.6	C
Mbango	144	E	27.8	D	Mpambanyoni	91	C	33.8	C	Mdlotane	75	B	58.6	A/B
Umzimkulu*	81	C	79	C	Mahlongwa	96	C	34	B	Nonoti	95	C	63.8	C
uMthente	81	C	40.6	C	Mahlongwana	91	C	45	B	Zinkwasi	97	B/C	75.5	A/B
Mhlangamkulu	92	C	19.8	C										

Reassessment of selected estuaries

The 2013 Orange Estuary EFR study updated the 2003 EWR assessment. The study was completed as part of the Atlas Project (ID 71598) for the Orange-Senqu River Basin (UNDP-GEF Orange-Senqu Strategic Action Programme). The Keurbooms Estuary, part of the Gouritz WMA, was not officially re-assessed. However, the estuarine team working on the project decided to gather additional field data after concerns were raised by various interested and affected parties. The uMdloti Estuary was first assessed with the Mhlanga Estuary in 2002 (DWAF 2003a). An intermediate assessment of the uMdloti Estuary was then conducted in 2007. These results were included in the classification of the 64 estuaries occurring within the Mvoti-Umzimkulu WMA. Reassessment of estuaries revealed few changes aside from minor changes in % MAR received and importance scores, which would influence the recommended ecological categories as well. The changes in % MAR received is likely due to more accurate flow data and monitoring and not likely due to increased abstraction in the time between assessments. The importance score of half of the reassessed estuaries improved while the other half decreased.

Sampling at Langebaan Estuary

Table 14 **Comparison of scores obtained from revised ecological water requirement studies of South African estuaries.**

Estuary	Original study							Updated study					
		EHI score	PES	Importance score	REMC	Level of study	Year completed	% of natural MAR	PES	Importance score	REC	Level of determination	Year completed
Orange	44	56	D	95	C	Rapid	2003	40	51 (D)	99	A or BAS	EFR	2013
Keurbooms	93	92	A/B	88	A/B	Rapid	2008	92.7	A/B		A or BAS	Desktop	2015
Zotsha		77	B	43	B	Rapid	2011	97	B	46.9	A/B or BAS	Desktop	2015
Umzimkulu	83	79	B	84	A	Intermediate	2011	81	B	79	B	Desktop	2015
Little aManzimtoti	233	38	E	37	D	Rapid	2011	133	C	34.4	C*	Desktop	2015
Mbokodweni		34	E	49	D	Rapid	2011	30	D	41	D	Desktop	2015
uMngeni		38	E	81	A	Rapid	2011	39	E	73.1	D	Desktop	2015
Mhlanga	158	68	C	69	B	Rapid	2003	33	E	70.3	B*	Desktop	2015
uMdloti	84 (83.8)	52 (41)	D	66.4 (69)	C (C)	Rapid (intermediate)	2002 (2007)	84	D	72.8	C*	Desktop	2015
uThongathi	101	49	D	61	C	Intermediate	2007	99	D	62.6	C*	Desktop	2015

Studies that contributed to the improvement of Ecological Water Requirement methods

The RDM method has followed a ‘learning by doing’ approach with adaptations incorporated by the estuarine experts involved with the development of the method. Some studies in particular stand out for their contributions to the improvement of the RDM method. These studies are presented chronologically in Table 15. EFR studies were initiated in 1997 and completed in 2000 for the Mhlathuze and Nhlabane estuaries, situated near Richards Bay on the KZN north coast). These studies were completed using the best methods available at the time as the Resource Directed Measures method was still under discussion. The Nahoon Estuary was initially planned as an EFR study and thus would not have included aspects under RDM methodology such as allocation of an Ecological Management Class, setting the Reserve for Water Quality or setting of RQOs. Due to timing the Nahoon Estuary was the first intermediate level assessment applied by DWS and thus had the secondary aim of testing the method.

Table 15 Ecological Water Requirement studies that have contributed to the development of the Resource Directed Measures method.

Date	Estuary	Contribution to the method development
1989	Great Brak	First EWR study for an estuary by allocating water release from the Wolwedans dam to keep the mouth open in spring / summer. Developed a comprehensive monitoring programme that was followed for 20 years.
1998	Swartkops	The study showed that the estuary reserve for water quality must be set for river inflow as this can be measured and monitored. Water quality included in all subsequent EWR assessments.
1998	Palmiet	Physical processes were summarized as abiotic states linked to flow ranges.
1998	Mhlathuze	This has been one of two studies which required a redefinition of the reference state. The reference state was not the natural state because of the alteration of the system due to the construction of Richards Bay harbour. This practise was later dropped as it did not allow for tracking ecosystem change.
1998	Nhlabane	Highlighted the value of water level data and mouth condition data collected for the same time period. This study also redefined the reference state as Nhlabane Lake no longer forms part of the estuary configuration.
2000	Mtata	First application of the official 1999 DWAF RDM method for estuaries. Clearly indicated that confidence of study influenced by available field data.
2000	Nahoon	Highlighted the importance of having salinity profile data together with river inflow data.

2001	Thukela	First assessment that recognized the EWRs of the marine environment and evaluated the role flow plays in the nearshore environment. This study followed a 2-tier approach in which 1st a wide range of flow scenarios were evaluated, followed by a focused assessment of a narrow range of dam development permutations. This study also indicated the robustness of the EHI when similar flow scenarios were considered in the second workshop and the same final health scores were assigned.
2001	Breede	Hydrological and 1-dimensional numerical modelling was coupled to predict estuary response. Subsequent monitoring indicated that the numerical modelling was very accurate in predicting low flow states in this estuary. This was also the first study in which fish catches were directly liked to measured salinity distribution and in turn linked to model results to predict changes in fish distribution.
2003	Tsitsikamma	The need for accurate low flow hydrological data and recommended consultation with a system analyst to calculate simulated run-off data was emphasised.
2004	St Lucia	Water balance model first tested for on estuarine lake. Monitoring requirements included for the first time. Study was co-funded by DEA and DWAF. From this study onwards realistic flow scenarios were considered for the catchment and also those that would achieve an ecological class above or below the present state.
2004	Orange	The need to simultaneously collect abiotic and biotic field data was emphasized. Coordinated sampling enables quantification of linkages between abiotic and biotic processes.
2004	Kromme	Version 2.0 (2003) of RDM method used for the first time. First study to use ecological specifications. Estuary was defined in two sections with the Geelhoutboom tributary evaluated separately to account for its importance.
2005	Olifants	This study indicated that in a large variable estuary the ideal conditions are not necessarily captured in a single low flow and high flow field survey.
2007	Keurbooms	Health of the estuary can be improved by addressing non-flow related activities such as habitat destruction and exploitation of living resources. First active link between EWR and Estuarine Management Planning process with the recommendations of the EWR leading to the development of a management plan.
2007	East Kleinemonde	The importance of daily flow and not monthly average flow data was highlighted for small temporarily open/closed estuaries where the response time is in days. Modelled freshwater inflows do not produce data at a fine enough time scale. Quantitative modelling approach using Stella also tested.
2007	Siyaya / uThongathi	Mouth status is a significant weak point in these assessments that can only be addressed if long-term flow and mouth state data (5 to 10 years) are available. Factors such as artificial breaching can confuse the links between flow and mouth status.
2007 /2008	Knysna	Present state and EWR considered for four separate compartments, the bay, middle reaches, upper reaches and the Ashmead channel due to the sensitivity to freshwater inflow reduction.

2008	Great Brak & Goukamma	The importance of cooperative governance between different management authorities in order to achieve national management objective goals and improve the health of the estuary was highlighted. Great Brak showed the importance of monitoring all the components (older studies did not include fish and birds) and measuring during all the seasons (previous studies only focussed on summer, while closed period during winter showed that the ecosystem was stressed). The study also taught us that just focussing on open mouth conditions as an indicator of health did not guarantee a well-functioning system. First pilot testing of Desktop assessment on Kaaimans, Knoetsie, Maalgate and Gwaing.
2012	Orange	First formal application of method to access flow requirement of the marine environment.
2012-2015	Gouritz WMA	Long-term data can elevate a Desktop/rapid level assessment to an intermediate level, e.g. Duiwenhoks. Incorporate fountains and seeps as important supporting habitats in EHI.
2012-2015	Mvoti-Umzimkulu WMA	Formal application of the desktop method. Also developed a detailed volumetric approach to access impact of waste water scenarios on the estuaries. Study clearly showed that small estuaries have very little assimilative capacity with regard to pollution, from the catchments and/or as form WW discharges. This is also the first time that estuaries were formally incorporated into the Classification process, highlighting the need for catchment-to-coast and coast-wide integration.

Lessons learnt from completed studies

From the completed studies some key learning points have emerged as summarised in Table 16. Each lesson is further described with examples in the section below.

Table 16 **Reserve determination studies that have contributed to the understanding of the effects of altered freshwater inflow on estuarine functioning with inputs from van Niekerk *et al.* (2012).**

Date	Estuary	Contribution to the understanding of changes in freshwater inflow on estuaries
1997	Thukela	River mouths have an important function in supplying nutrients and sediments to the nearshore environment. The marine environment also has a requirement for freshwater inflow.
1997	Olifants	Freshwater requirements of the large supratidal salt marsh areas were not understood. The hypothesis was that these areas require a 1-in-2 year flood. Subsequent research indicated that the dry saline habitat was dependent on the groundwater
1998	Palmiet	Highlighted the existence of the semi-closed mouth state.
1998	Nhlabane	Groundwater input from surrounding dune areas (caused by artificial lake levels) can increase water level in the estuary resulting in breaching of the estuary mouth.
2000	Mtata	Seasonal flow patterns altered by hydroelectric plant with higher flow in winter compared to summer. Study showed that the EWR must mimic the natural flow distribution to ensure ecosystem structure and function.
2001	Breede	Indicated the resilience of a large freshwater estuary to flow reduction. This system was not as sensitive to flow reduction as some of the small temporarily open/closed estuaries.
2002	Mdloti and Mhlanga	Increased flow as a result of input from WWTWs causes eutrophic conditions and a decline in estuary health due to unnatural frequent breaching of the mouth.
2004	Orange	The study highlighted the impact of elevated flow and the need for mouth closure, e.g. back flooding to reduce soil salinity.
2006	Siyaya	Understanding the effect of freshwater inflow on sedimentation patterns is particularly important for predicting future responses in the small KZN estuaries.
2007	East Kleinemonde	Small estuary that is naturally nearly permanently closed and therefore not that sensitive to flow reduction. Floods play a significant role in maintaining/controlling their mouth regime.
2007/2008	Knysna	The marine dominated, large bay section of Knysna was not sensitive to changes in freshwater inflow. However the upper reaches of the estuary were more sensitive.
2008	Kromme	Showed the need to evaluate from the reference state. Marine-dominated Kromme Estuary was buffered against impact of large dam development as it received limited inflow during average conditions. Dam not as big an impact as anticipated.
2008	Great Brak	Water releases from dams can be used to improve estuary health. Releases from Wolwedans dam kept the mouth open at an important time of the year spring / summer promoting salt marsh growth and fish and mudprawn recruitment from the sea into the estuary. However, detailed monitoring has shown that the dam releases

		cannot mimic natural flood events that remove organic material from the system. The organic load results in poor water quality conditions during the closed period. Macroalgal blooms indicate deterioration in water quality which nutrient measurements did not show.
2008	Goukamma	Rapid study with an once off survey water quality indicated that the system was in a very good state, subsequent monthly sampling showed that adjacent agriculture was stimulating primary production in the low flow state leading to eutrophication and low oxygen in the estuary.
2009	Swartvlei	Detailed mouth condition records are necessary as it is difficult to determine the reference / natural condition if artificial breaching has occurred. The water balance models of large lake systems are generally sensitive to assumptions around breaching levels as a result of the low MAR to estuary volume ratio.
2009/2010	Berg	This is possibly the most diverse estuary in the country because of the large freshwater floodplain areas and pans. This study required the incorporation of flood requirements for the floodplain habitats for vegetation and birds.
2010	Bushmans	Although a naturally saline system, flow reduction impacted estuary health and removal of inefficient farms dams and weirs was recommended. While, naturally saline systems have a relatively low baseflow requirement, if this is removed the estuary functions as a side arm of the sea and production decreases.
2012?	Sundays/Great Fish	Consistent baseflow as a result of the Orange River transfer system and agricultural return flow increases nutrient input resulting in algal blooms and reed growth.
2012-2015	Mvoti-Umzimkulu WMA	This study showed that small estuaries have very little assimilative capacity with regards to pollution, from the catchments and/or from wastewater discharges. Removing one source would not necessarily help with restoration if remaining inputs from the catchment are still high.
2015	Klein Brak	Some impacts on freshwater inflow are reversible, e.g. removal of weirs in the Klein Brak Estuary would improve low flow conditions and estuary health.

1. Each estuary is unique in terms of its ecological water requirements

Estuaries require adequate freshwater inflow to maintain them in a good ecological state. Small estuaries are more sensitive to flow reductions (van Niekerk 2007). Low flows are usually related to closed mouth conditions and high flows and flooding events to open mouth conditions. However, the actual flow magnitudes are specific to each estuary and have little relevance to others. The Great Brak Estuary, for example, will close at a flow < 0.3 m^3s^{-1} whereas the Mgeni Estuary on the east coast will close when flow is approximately 1 $m^3.s^{-1}$. Mouth functioning is determined by wave climate and tidal regime at an estuary's location, and associated cross-shore and long-shore sediment transport.

Estuaries on high energy coastlines experience mouth closure within less than a month of flow decreasing below the estimated flow needed to maintain open mouth conditions (van Niekerk *et al.* 2012). Protected estuary mouths, however, may only experience closure after a few months. Very small estuaries such as Little Amanzimtoti and Mbokodweni on the east coast have mouth opening and closure occurring over very short time scales, often in less than a day. Sand berm accretion is slower in more protected systems. According to Perissinotto *et al.* (2004) the height of a sand berm at the mouth of an estuary in KZN can reach its maximum height in seven days. Data for the Great Brak Estuary shows that its take up to four months to reach similar maximum levels (van Niekerk *et al.* 2012).

2. Water can be released from dams to supply ecological water requirements, but cannot mimic the entire natural flow regime

The Great Brak Estuary and Kromme Estuary receive freshwater via releases from upstream dams. The Wolwedans Dam, situated upstream from the Great Brak Estuary, reduced river inflow and caused extended closed mouth conditions. A management plan was designed to imitate the natural functioning of the system, maintaining an open mouth in spring and summer (DWA 2009a). This involved releasing water from the dam in September to April as well as artificial breaching of the mouth in order to simulate the role of flooding in scouring the mouth open. Open conditions are essential for maintaining the estuary's health as it promotes salt marsh growth and the recruitment of fish and invertebrates.

The Wolwedans Dam upstream of the Great Brak Estuary, Western Cape

However subsequent sampling of the closed mouth state indicated that while dam releases can maintain open mouth conditions, they cannot flush the build-up of organic material from the system. During the closed state, decomposition of this residual organic material can cause oxygen stress to higher trophic levels such as fish. Dam release cannot mimic natural flood patterns that provide a cue to attract juvenile fish and invertebrates to the system or reset sediments. Most dams in South Africa were not designed to release floods.

Two dams (Churchill and Mpofu) upstream of the Kromme Estuary have a combined storage capacity of roughly 133% of the estuary's MAR (100 x 10^6 m^3) (Bate & Adams 2000). Aside from overflow from the Mpofu Dam during floods the only freshwater currently supplied to the estuary is that allocated for ecological purposes (i.e. controlled releases of freshwater). This allocation is significantly less than the freshwater requirements of the estuary estimated to be approximately 11 x 10^6 m^3 or 8.9% of the MAR (DWA 2009). Release of water equivalent to a 1-in-2 year flood from the Mpofu Dam above the Kromme Estuary had little effect on the saline system and Bate and Adams (2000) concluded that consistent baseflow was required to establish a salinity gradient. Studies such as this on the ecological water requirements have ensured that further licenses are not issued in stressed catchments or where the EWRs are high.

3. Floods are needed to flush out and reset estuaries

Floods are important in resetting the sedimentary process in an estuary and removing excess macrophyte growth. Along South Africa's wave dominated coast, more marine sediment enters an estuary on the flood tide than leaves it on the ebb tide. Catchment sediments also accumulate in the upper and middle reaches during normal flow conditions. Floods play an import role in maintaining the sediment equilibrium in an estuary.

Reed encroachment is probably one of the most common responses to a reduction in freshwater inflow. Catchment clearing, removal of riparian vegetation and nutrient enrichment all play a role in sedimentation, shallowing and accelerating reed encroachment. When these floods have been attenuated due to dam construction this no longer happens. A classic example of accelerated sediment processes and reed encroachment is in the highly degraded Siyaya Estuary in KZN.

Reed encroachment evident within the Mcantsi Estuary, Eastern Cape

Extensive siltation from mismanagement of the catchment and reduced freshwater inflow as a result of forestry activities has resulted in increased mouth closure, reduced water depth and reed encroachment (Begg 1978; DWAF 2006). From aerial photographs it was determined that reed swamp, dominated by common reed *Phragmites australis,* has been expanding at a rate of 0.15 ha per year (Benfield 1984). The Siyaya Estuary is a protected area under the jurisdiction of Ezemvelo KZN Wildlife and thus should be rehabilitated to its best attainable state (DWAF 2006). This study illustrated the importance of understanding the effect of freshwater inflow on sedimentation patterns, particularly for predicting the future responses of the small KZN estuaries.

4. Increased flow, for example from wastewater input or agricultural return flow, increases mouth breaching resulting in unstable conditions in temporarily open/closed estuaries

Urbanisation and sewage discharge from WWTWs has increased freshwater inflow to many of the small KZN estuaries. Increased freshwater inflow has increased the frequency of mouth breaching resulting in an unstable system with low biotic diversity and biomass (DWAF 2002; 2003; Perissinotto *et al.* 2004). As a result the estuary has changed from a predominantly closed estuary to a predominantly open system. Because the estuary is perched above mean sea level, when opened it drains resulting in low water levels exposing most of the floodplain. Important fish and invertebrate habitats are lost, in particular the closed phase nursery habitat for fish. The reed beds are left high and dry and the periphyton on which the fish feed can no longer grow. Reduced reed productivity results in a loss of detrital input to the estuary which influences the entire food chain (Whitfield 1980). Diversion of effluent to the uMngeni catchment has been suggested to restore the health of Mhlanga Estuary.

5. Deterioration in water quality is a growing concern

The water quality of South African estuaries is declining; mainly due to input of sewage effluent and agricultural return flow. Estuaries that occur in urban areas have particularly poor water quality. The health of the small estuaries in KZN have been seriously comprised by wastewater and other pollution inputs. It was noted (DWA 2013) that the assessment of nutrient discharge into estuaries from WWTWs should consider the impact on the receiving environment rather than relying on adherence to permitted discharge levels.

Agricultural return-flow and nutrient enrichment has been identified as a problem in a number of estuaries around the country, e.g. Olifants, Berg, Breede, Gamtoos and Sundays. Persistent phytoplankton blooms indicating eutrophic conditions have been recently described for a number of estuaries (Snow *et al.* 2000; Kotsedi *et al.* 2012; Kaselowski & Adams 2013). Macroalgal blooms in Great Brak and East Kleinemonde estuaries indicate deterioration in water quality thought to be from leaking septic tanks (van Niekerk *et al.* 2008; Nunes & Adams 2014). In TOCEs open mouth conditions and tidal exchange is important for maintaining water quality.

Eutrophic conditions and litter present at the East Kleinemonde Estuary, Eastern Cape

Deterioration in water quality is increasing concern not only in temporarily open/closed estuaries, but also in open flushed bay systems such as Knysna which is ranked as the most important estuary in the country for biodiversity conservation. The Knysna Estuary was described to be on a negative trajectory of change due to non-flow related issues (DWA 2009). The lower reaches of the estuary around the Ashmead Channel experience poor water quality due to inputs from the Knysna WWTW as well as runoff from urban areas. This results in the proliferation of macroalgae such as *Ulva* and *Cladophora* spp. Although an oligotropic estuary by nature, macroalgal blooms are becoming increasingly more common in the estuary.

6. The importance of groundwater input to South African estuaries is unknown

Groundwater input has been identified as important in the functioning of a few estuaries (e.g. St Lucia) but has not been investigated in detail in other estuaries. The EFR study of Nhlabane Estuary illustrated how groundwater input from surrounding dune areas (caused by the artificial damming of Nhlabane Lake) can increase water levels in the estuary resulting in breaching of its mouth (DWAF 2000). An early EWR study on the Olifants and Orange estuaries identified that the freshwater requirements of the large supratidal salt marsh areas were not understood. The hypothesis was that these areas require a 1-in-2 year flood to maintain suitable salinity and moisture conditions for plant growth. Subsequent research in the Olifants (Bornman *et al.* 2008) and Orange estuaries (Shaw *et al.* 2008; Bornman & Adams 2010) showed that groundwater was essential for plant survival and that freshwater inflow and flooding influenced depth to groundwater and salinity. The Goukou Estuary study showed the importance of fountains and seeps in maintaining micro-habitats along the length of the system that provides important refugia for invertebrates and fish such as eels.

7. The offshore marine environment also has an ecological water requirement, but this does not form part of the current legal framework

Estuarine habitats often extend beyond the mouth of a system and offshore habitats in the marine environment require input (e.g. nutrient and sediment) from catchments (watersheds). The Thukela Estuary study (DWAF 2004b) was the first to recognize the ecological water requirements of the nearshore environment. The Thukela River has a high mean annual sediment load of about 9 million ton, corresponding to a sediment yield of 400ton/km^2 per annum (DWAF 2004b). Regular large floods are needed to ensure the deep mouth is scoured ensuring supply of sediment to the offshore environment. The recent Orange Estuary study (Van Niekerk & Lamberth 2013) provided a detailed evaluation of the freshwater flow requirements of the offshore environment. The study followed the method developed as part of Van Ballegooyen *et al.* (2003), but followed a more scenario based approach similar to the estuary EWR method. Sediment supply from the Orange River catchment maintains the beaches north of the system providing habitat for flatfish. Large floods are required to remove the islands occurring in the braided system and to flush the tidal-basin area and sandbar out to the ocean. Bremner *et al.* (1990) estimated that 81 million tonnes of sediment was scoured from the estuary during the 1988 flood. Floods are necessary for maintaining the long-term dynamic equilibrium of the system as sediment processes operate at different scales from hydrodynamic, biogeochemical and biological processes. Sediment transport and other morphological responses can occur at hourly to decadal and even longer time scales. Accretion and erosion of subtidal areas (which can result in changes in volume) often occur at shorter time scales, whereas intertidal areas often vary over mid-range time scales. Presently the estuary receives 60% of its natural MAR which has resulted in a reduction in large flood frequency to one in 10 years. This large change in flood regime will have a significant impact on estuarine habitat.

As part of the Mvoti-Umzimkulu WMA project the Umkhomazi and Mvoti estuaries are considered of high functional importance because they form part of five key systems (Mfolozi, Mvoti, uMngeni, uMkhomazi, Umzimkulu) that supply sediment, nutrients and detritus to the coasts. Other river mouths may also play less of a role as they occur along more nutrient rich coasts. Although not within the scope of the RDM method it was suggested that the impact of further dam development on the nearshore marine environment be evaluated to ensure all ecological processes and related ecosystem services (e.g. beaches, coastal buffers against storms, the KZN prawn fishery) are considered (DWA 2014).

The large sandberm at the Mvoti River mouth, KwaZulu-Natal

The omission of the marine environment from the early South African methods was as a result of the sectoral management of water resources in South Africa. Government departments tend to only focus on their specific mandate (in this case the DWS jurisdiction stops at the mouth of estuaries), while the coastal, offshore and marine environment was mainly the responsibility of the Department of Environmental Affairs and Tourism (Taljaard *et al.* 2003). The proposed existing method has been tested on the Orange and it is recommended that similar EWR assessments be conducted on the twenty largest catchments in South Africa.

8. A catchment to coast approach integrated water management approach is necessary to ensure connectivity

Mouth closure caused by reduced flow causes loss of connectivity between nursery habitats thus affecting recruitment of invertebrates and fish. Coastal squeeze caused by global climate change (i.e. rising sea levels and storm surges) will further limit connectivity and reduce the resilience of coastal environments (Cushman *et al.* 2010). Changes in freshwater inflow alter marine fish catch composition therefore reducing the economic return of fisheries (Lamberth & Turpie 2003; Lamberth *et al.* 2009). A few fish species are able to recruit into estuaries during closed conditions through overwash events in which larval fish assemblages move over the berm (Cowley & Whitfield 2001; Perissinotto *et al.* 2004; Whitfield & Bate 2007). This has been noted at South Africa's East Kleinemonde Estuary where mainly estuarine-associated marine fish species such as *Rhabdosargus holubi* have been found in the nursery areas (Cowley *et al.* 2001). Coastal connectivity is currently not captured in any governance frameworks.

A weir at the Nhlabane Estuary, KwaZulu-Natal

9. Co-operative governance is required to address non-flow related impacts and improve estuary health

Estuaries are dynamic systems and have the ability to adjust to adverse pressures. In many instances estuary health could be improved through simple, relatively inexpensive mitigation measures such as the removal of old dysfunctional weirs. In other instances development or the need for storage dams prevents the rehabilitation of estuaries to their pristine, natural state. The Uilkraals Estuary, for example, receives 70% of its MAR because of abstraction from the Kraaibosch Dam situated upstream of its mouth (Anchor Environmental Consultants 2012). Removal of the baseflows and the discharge of effluent into the estuary has, however, resulted in a decline in the estuary's health. Modelling of future scenarios illustrated that removing invasive alien plants from the entire catchment would restore much of the original base flow thus assisting in maintaining an open mouth state which in turn would help minimise sewage-related problems.

The small, almost permanently closed East Kleinemonde Estuary receives almost all of its natural MAR (96%) (van Niekerk *et al.* 2008). The estuary has been targeted to be a Desired Protected Area by the National Biodiversity Plan for estuaries and thus should be rehabilitated to an "A". The Best Attainable State for the East Kleinemonde Estuary is, however, a B as the small system is sensitive to the surrounding urban development (i.e. fishing pressure, nutrient input, riparian developments, noise disturbance and loss of aquatic habitat due to boating).

The Integrated Coastal Management Act (Act 28 of 2008) ensures that co-operative governance should take place between different management authorities to improve the health of estuaries in South Africa. Because estuaries are governed by a variety of authorities, from national to local level, estuary management must allow for a dynamic process that facilitates integrated cross-sectorial planning and implementation including stakeholders involved in land-use planning, management of freshwater and marine resources, amongst others (DEA Guidelines for EMPs 2015). The ICM Act sets out specific requirements for the development of a National Estuarine Management Protocol for South Africa (Chapter 8), as well as the development of individual estuarine management plan.

10. Field and long-term data are needed for high confidence ecological water requirement studies

The confidence of an EWR study is dependent on the availability of data. Often funding is too limited to enable sufficient detail to be included thus producing low confidence results (Huizinga *et al.* 2003). Accurate hydrology is of particular importance with some studies being delayed or repeated due to inaccurate hydrological data. Field data should be collected concurrently so that the relationships between flow, hydrodynamics, sediment dynamics, water quality and biotic response can be determined. Due to budgetary constraints some studies exclude certain components, decided upon by the specialists. The weighting of the other components was then adjusted to produce the present ecological status score. For example water quality and birds were not assessed as part of the rapid determination for the Tsitsikamma Estuary (DWAF 2003). Microalgae were not assessed as part of the Siyaya EWR study (DWAF 2006). This practise have largely been discontinued, in more recent studies assessment have been made of all components, albeit of a very low confidence for components that were not deemed critical to the study.

Field sampling is not always conducted for rapid studies and thus studies may be based on outdated data, such as biological assessments by Begg (1978, 1984) for KZN estuaries. Historical data may no longer be representative of the present state of the estuary and thus is not always useful for determining ecological water requirements (Taljaard *et al.* 2003). Site visits are required before initiating An EWR study as specialists may not have previous experience with the system. In the Siyaya reserve study specialists adjusted their scores after visiting the estuary in its current condition (DWAF 2006). Although field surveys were completed during both high and low flow periods of the Olifants Estuary the true variability of the system was not captured. Atypical rain patterns during the study period of the Breede Estuary prevented the measurement of the extent of saline intrusion typically encountered during low flow periods. However in both studies hydrological and numerical modelling assisted with the prediction of the occurrence and duration of the low flow state in the absence of measured data.

In order to make an accurate assessment of health temporarily open/closed estuaries must be sampled in both closed and open mouth states. The Great Brak Estuary, for example, has been monitored for many years, but only once all biotic aspects were considered, particularly the fish, could an accurate assessment be made. Daily mouth observations and flow data are required for small temporarily open/closed estuaries. The RDM method currently analyses changes in runoff on a monthly time scale. Unfortunately this time scale is completely inadequate for small estuaries that respond to daily flow events. Small estuaries such as East Kleinemonde and Little Amanzimtoti open for a day at a time (van Niekerk *et al.* 2008; DWA 2011). The high variability of these systems is not addressed when monthly average changes in run-off are considered. Often artificial mouth breaching will confuse the understanding of freshwater flow and mouth condition unless accurate records are kept.

11. Monitoring must take place in a strategic adaptive management cycle

EWR studies provide an update and collation of available information on an estuary. Recently the completed studies have formed the basis for the development of EMPs. The quality of the management plan is directly linked to the availability of data from an EWR study. Most completed EWR studies emphasised the need to increase monitoring, such as water level recording, continuous flow gauging of river inflow to the estuary, mouth observations, longitudinal and vertical salinity distributions and nutrient concentrations as well as selected biotic components. Reassessing individual systems on a five year basis, as stipulated by the RDM method, would ensure that uncertainties are addressed, however little of this monitoring has taken place.

For some estuaries RQOs have been specified as part of the Water Resource Classification or the EWR process. These objectives provide the targets or 'thresholds of potential' concern against which to monitor and assess ecological health. Monitoring is needed to assess whether the EWR reserve is achieving the desired state (i.e. health category) and associated ecological conditions. Each EWR report identifies the resource monitoring required for selected abiotic and biotic components and the temporal and spatial scale of monitoring. The DWS has started a National Estuary Monitoring Programme where Tier 1 monitoring focuses on abiotic parameters and Tier 2 is the monitoring identified in the RDM / EWR study reports (Figure 6, Cilliers & Adams under review).

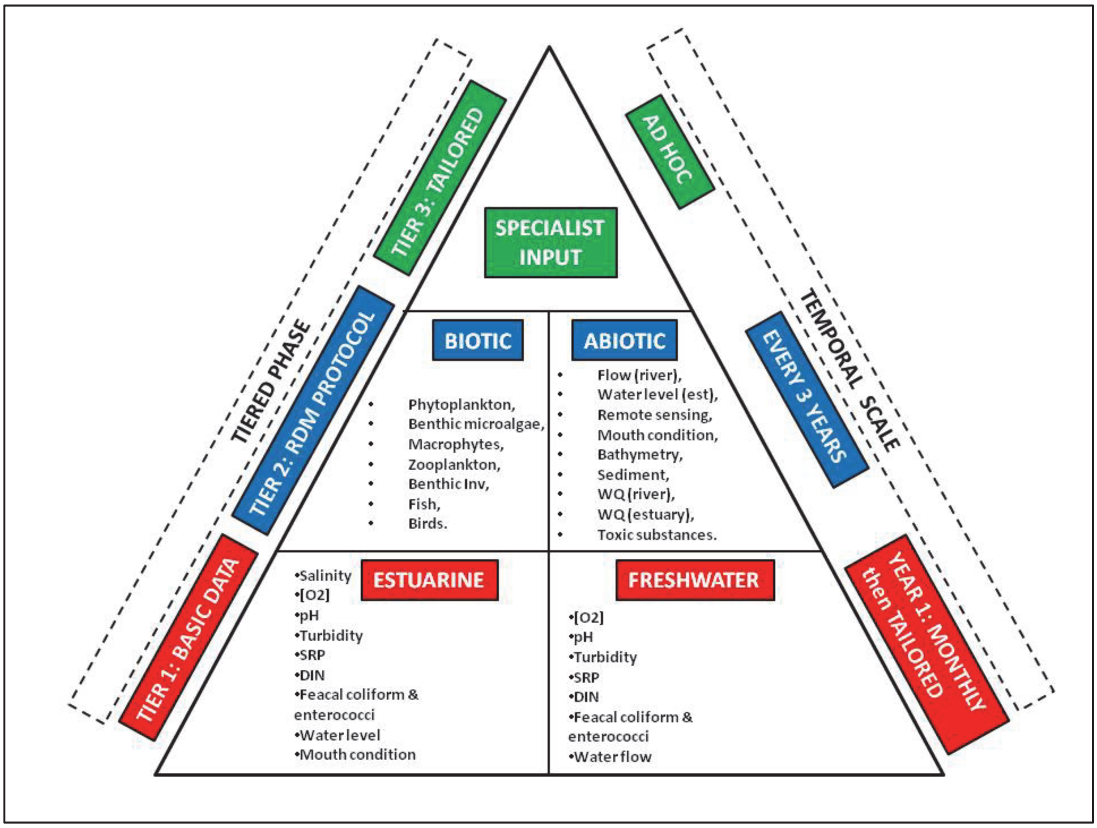


Figure 6 **The National Estuarine Monitoring Programme for South Africa.**

12. The tools developed to determine the ecological water requirements of an estuary are now being used to meet other legislative requirements

The procedures developed to assess the PES of an estuary have been applied on a national basis to determine the “Ecosystem Status” and “Ecosystem protection level” for estuaries in the 2012 National Biodiversity Assessment. The two headline indicators were set based on the occurrence of A and B category estuaries. The National Estuary Biodiversity Plan (Turpie *et al.* 2012) also relied on the output of these tools to determine which estuaries in South Africa require prioritisation for protection to meet international biodiversity targets.

Evaluations of the impact of wastewater discharges on estuaries are currently being assessed using the EWR method for both the DEA and DWS, with DEA at present working within the A to F scale developed by DWS. By aligning the assessment methods and output (i.e. estuary health status assessments, recommended future condition, flow and water quality requirements) across sectors, results can serve a multitude of purposes across a range of legislative requirements. This assists with integrating study results and with day-to-day planning and management of estuaries.

A framework for capturing estuarine data

The implementation of EWRs produces scientific data that adds to our knowledge of individual estuaries. Abiotic and biotic data are obtained as per the components of the EHI. Table **17** details the baseline information requirements for high confidence studies. The type and amount (e.g. once-off, seasonal) of data produced are dependent on the level of the study. Lower confidence studies usually only involve once-off site visits that may not reflect the variability of the system. Although, even a snap shot of the present health and functioning of an estuary can bench mark potentially outdated historical data. The wealth of robust scientific data obtained from completed EWR studies is currently inaccessible, or at best captured as raw data in appendixes of reports. The data requires capturing within a framework to ensure that it can be easily distributed for use in research and for management purposes. Data extracted from EWR reports and appendices should be collated with data obtained from the National Estuary Monitoring programme. This would enable an efficient storage system that could be maintained by DWS. It is sensible to manage the data obtained from EWR reports together with long-term monitoring data rather than as separate entities as they may become lost across management divisions.

Table 17 **Data obtained from Ecological Water Requirement studies.**

Component	Baseline information requirements for high confidence
Hydrology	Primary catchment delineation (true watershed)
	Measured river inflow data (gauging stations) at the head of the estuary over a 5-15 year period
	Measured rainfall data in the catchment (or in a representative adjacent catchment)
	Hydrological parameters (evaporation rates, radiation rates)
	Flow losses (e.g. abstraction, impoundment) and gains (e.g. discharges, transfer schemes)
	Flood hydrographs for reference condition
Bathymetry	Bathymetric/topographical surveys including berm height, cross sections at 10-50 m in the mouth region, cross section profiles at 500 m to 1000 m intervals upstream of the mouth, and floodplain topography (preferably done with Lidar)
Hydrodynamics	Continuous water level recordings near mouth of the estuary (or daily mouth observations)
	Water level recordings at 2-6 stations along the length of the estuary over a spring and a neap tidal cycle (i.e. at least a 14 day period)
	Long term data on daily mouth state (open/closed/overtopping) for temporarily open/ closed estuaries, particularly in systems that have a semi-closed mouth state
	Data on wave conditions
	Aerial photographs which include the breaker zone near the mouth.
Sediments	Sediment grabs samples collected using a Van Veen or a Zabalocki-type Eckman grab (to characterize recent sediment movement) for particle size analyses, along entire estuary at 500 to 1 000 m intervals
	Sediment core samples collected using a corer (for historical sediment characterization) at intervals similar to cross-section profiles (see bathymetry) or where considered appropriate by sediment specialist; collected at 3-6 year intervals, as well as after flood events
	Sediment load at head of estuary (including detritus component – particulate carbon/loss on ignition)
Water quality	Quarterly/monthly longitudinal salinity and temperature profiles (in situ) collected over a spring and neap tide during high and low tide with a focus on the end of low flow season and the peak of high flow season.
	Quarterly/monthly longitudinal water quality measurements (i.e. system variables, and nutrients) taken along the length of the estuary (surface and bottom samples) on a spring and neap high tide with a focus on the end of low flow season and the peak of high flow season.
	Measurements of organic content and toxic substances (e.g. trace metals and hydrocarbons) in sediments along the length of the estuary
	Water quality (e.g. system variables, nutrients and toxic substances) measurements for river water entering at the head of the estuary
	Water quality (e.g. system variables, nutrients and toxic substances) measurements for near-shore seawater

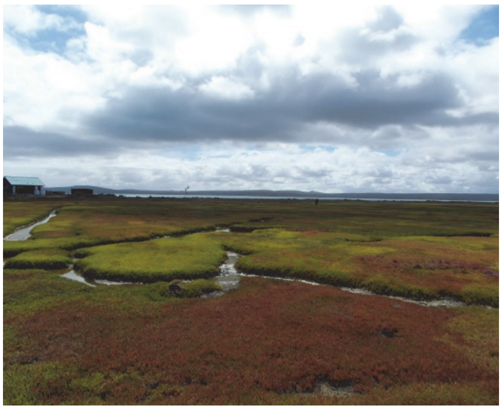
Microalgae	Data on relative abundance of dominant phytoplankton groups, i.e. flagellates, dinoflagellates, diatoms and blue-green algae, during typical high and low flow conditions.
	Chlorophyll-a measurements taken at the surface, 0.5 m and 1 m depths, under typically high and low flow conditions or open and closed mouth conditions.
	Intertidal and subtidal benthic chlorophyll-a measurements
	Along with measures of water salinity, inorganic nutrients, sediment particle size and total sediment organic matter.
Macrophytes	Aerial photographs of the estuary (ideally 1:5000 scale) reflecting the present state, as well as the reference condition (earliest year available). A GIS vegetation map of the estuary indicating the present and reference condition distribution of the different macrophyte habitats (e.g. salt marsh, mangroves, reeds & sedges).
	Number of macrophyte habitat types, identification and total number of macrophyte species, number of rare or endangered species or those with limited populations documented during a field visit. The extent of anthropogenic impacts (e.g. trampling, harvesting) must be noted
	Permanent transects (fixed monitoring stations that can be used to measure change in vegetation in response to changes in salinity and inundation patterns) set up along an elevation gradient: Measurements of percentage plant cover of each plant species in duplicate quadrats (1 m^2). Measurements of sediment salinity, water content, depth to water table and water table salinity. Usually completed where intertidal and supratidal salt marsh occur.
Invertebrates	Species and abundance of zooplankton, based on samples collected across the estuary at each of a series of stations along the estuary.
	Benthic invertebrate species and abundance, based on subtidal grab samples and intertidal core samples at a series of stations up the estuary, and pump sampling or counts of hole densities.
	Macrocrustacean species and abundance, based on sampling at each station using a benthic sled with flow meter, prawn/crab traps, and appropriate gear for shoreline
	Measures of sediment characteristics at each station
Fish	Species and abundance data of fish, based on seine net and gill net sampling at about 0.5-2 km intervals along the estuary, including all habitat types, e.g. *Zostera* beds, prawn beds, sand flats, and salinity ranges (with at least one sample sets in the 0 to 1 ppt reach of the system). These data should be available for four seasons of the year, or for low and high flow periods in a series of years.
Birds	One year of monthly counts of all water associated birds, by species, for the whole estuary, preferably separated into counting areas and/or a series of at least 10 years of summer and winter counts, in addition to historical data on the same.

Conclusion

Changes in freshwater inflow alter the dynamic nature of estuaries and the temporal and spatial heterogeneity to which the biota have evolved. The manner in which estuary characteristics are influenced by freshwater inflow is often not the result of a single flow event, but rather that of characteristic flow patterns occurring over weeks or months. The strong longitudinal gradients of abiotic characteristics and changes in response to tides and freshwater inflow influence the biotic composition and function. Every estuary has its own unique factors such as size and scale which largely determines its EWR. For example large estuarine lakes show changes in water level and salinity on annual temporal scales whereas TOCEs show changes on a monthly time scale (van Niekerk *et al.* 2012).

The development and application of the EHI to determine the present state of an estuary has been important in identifying impacts in estuaries and highlighting important processes that require monitoring. Assessment of the EWRs has ensured that further licenses are not issued in stressed catchments or where the EWR are high, e.g. Sout, Matjies, Noetzie estuaries. In the temporarily open/ closed Mhlanga Estuary, KZN, diversion of sewage effluent to the uMngeni catchment will take place in an effort to restore the health of that estuary. However the pressure for water in urban areas means that the health of some systems will never be improved, e.g. Kromme Estuary where dams in the catchment supply Nelson Mandela Bay and Umgeni Estuary (water supply for Durban) and Berg Estuary (water supply for Cape Town). In 2010 the ecological water allocation was not made from the Wolwedans Dam to the Great Brak Estuary because of the drought and low dam levels.

Globally implementation of EWR studies have been hampered by cost expertise, an absence of long term monitoring datasets and an inadequate understanding of the effect of changing freshwater inflow on estuaries (Moore 2004; Montagna *et al.* 2013). In South Africa current legislation and institutional and governance arrangements should allow for the effective management of estuaries (Adams *et al.* 2002; Lamberth *et al.* 2008; Adams 2014). However these activities are under-resourced and under budgeted.



Once determined implementation of EWRs is difficult, especially in catchments where water has been fully allocated. Reserving water in stressed catchments would require a reduction by reducing entitlements, finding additional water resources, or introducing efficiency gains (Lotz-Sisitka & Burt 2006). Protection and sustainable use of water resources has often been deemed unnecessary and the RDM method has been seen as impeding development and delivery of services (King & Pienaar 2011).

Climate change can be viewed as an additional form of anthropogenic alteration acting as an accelerator of ecosystem change. Analysis of climate change effects showed that the numerous small, perched (estuary volume decrease by 50 to 90% when open to sea) temporarily open/closed estuaries on the east coast would have an increase in open mouth conditions, a decrease in retention time and a related decrease in primary productivity and nursery function as a result of increased runoff. In contrast, reduced run-off to the west coast estuaries would increase mouth closure. To ensure healthy estuaries resilient to change, implementation of the EWRs as set by the National Water Act and protection / rehabilitation of the estuarine functional zone were identified (van Niekerk & Turpie 2012). The integration of climate change effects into plans and policies dealing with management and governance of estuaries is essential.

In conclusion South Africa's holistic approach to determining EWRs for estuaries is at the forefront of methods internationally. The procedure is well documented and soundly embedded in an understanding of the structure and function of South Africa's estuaries. The use of multidisciplinary scientific teams and panel workshops are integral to the method and are a strength. Failure to support the process with adequate data is a potential weakness. This study has shown that the EWRs have been assessed for approximately 40% of South Africa's estuaries and that important lessons have been learnt from these studies. A learning-by-doing approach has ensured that the methods used to assess the EWRs of South Africa's estuaries have improved over time.

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