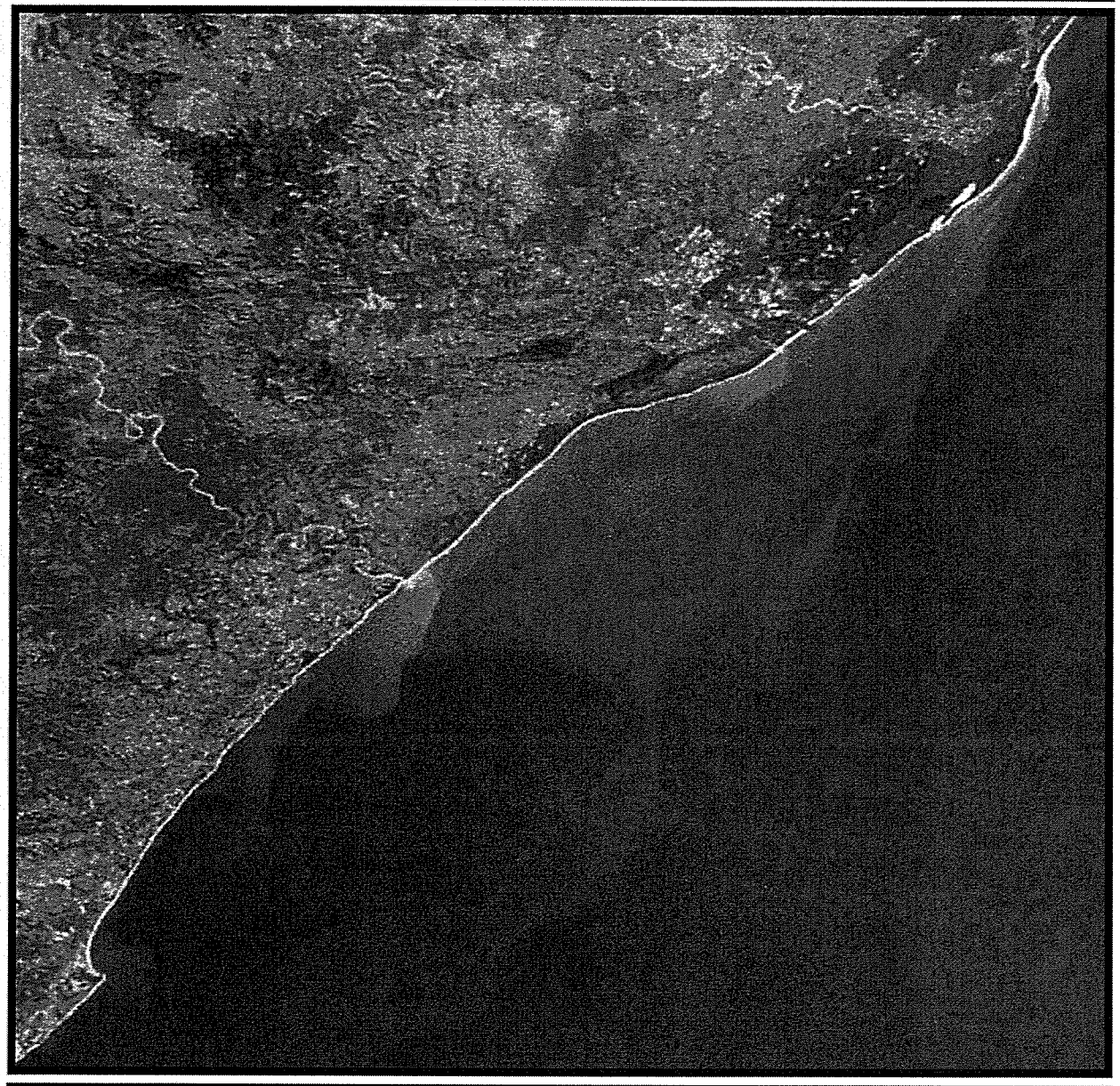
Freshwater Flow Dependency in South African Marine Ecosystems:

A Proposed Assessment Framework and Initial Assessment of South African Marine Ecosystems



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WRC Report No KV 191/07
July 2007

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This report is published by and obtainable from

Water Research Commission
Private Bag X03
Gezina
0031

The publication of this report emanates from a project entitled: *Freshwater Requirements of the Marine Environment: A Proposed Predictive Approach to Assessment* (WRC project no K8/509).

CSIR report number: CSIR Report CSIR/NRE/ECO/ER/2006/0196/C

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ISBN 978-1-77005-585-8

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Scope of Work

As a component of the Water Research Commission's (WRC) unsolicited research programme, the CSIR has proposed a project to:

- to the extent appropriate, develop a framework and/or methods to assess and predict the potential impacts of the reduction in freshwater flows into the marine environments;
- undertake, on a national scale, a preliminary assessment on where the reduction of freshwater inflows and associated fluxes (nutrient and sediments) into coastal marine environments is likely to have a significant impact on marine ecosystems; and
- based on the outcomes of the above, provide guidance on future studies and/or research required to fully develop and implement such a predictive assessment capability.

The ultimate purpose is to develop a realistic and cost-effective method to assess the impact of the reduction of freshwater inflow to the marine environment.

This report has been split into two parts:

- **Part I,** that introduces the study and proposes an appropriate framework for:
  - undertaking an initial assessment of the role of freshwater inflows and associated fluxes in coastal and shelf marine ecosystems of South Africa, and ;
  - managing the potential effects of changes in these fluxes into marine ecosystems;
- **Part II,** comprising an initial assessment of the role of freshwater in South African marine ecosystems. This section also provides guidance on the nature and extent of the studies and/or research required to ensure that the potential impacts of the reduction in freshwater flows into the marine environments are adequately assessed when considering the desirability of proposed developments potentially resulting in such a reduction of freshwater inflow.



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February 2007

Summary

Introduction

Freshwater is scarce in many regions of the world and, in this regard, South Africa is no exception. The competition for water resources, particularly those required to sustain estuarine and open coastal marine systems, relate largely to escalating conflicts between development, environmental protection and management of natural resources, the growing numbers of freshwater users and conflicts among them, and multiple authorities managing the resource. Consequently for adequately informed decisions to be made, there is a growing need to better understand the impact of altered flows of fresh water on estuarine and (coastal and shelf) marine systems.

It has long been recognised in South Africa that developments leading to the reduction in freshwater flows into the river/estuarine systems have a significant impact on the associated river/estuarine ecosystems. Consequently, appropriate assessment frameworks and methods have been evolved to assess the potential impacts of the freshwater reduction in South African river, wetland, groundwater and estuarine environments. However, there is a growing realisation and acceptance that developments leading to the reduction in freshwater flows in South African river/estuarine systems also have a potentially significant effect on marine ecosystems, particularly along the east coast of southern Africa. Many aquatic species of socio-economic importance are supported by these environments and freshwater inputs may have a strong influence on their abundance.

In contrast to river, wetland, groundwater and estuarine environments where appropriate assessment frameworks and methods have been evolved to assess the potential impacts of the freshwater reduction, no similar assessment framework or method presently exists to assess the potential impacts of the reduction in freshwater flow into South African marine environments.

Purpose of the Study

In response to the above, as a component of the Water Research Commission's (WRC) unsolicited research programme, the CSIR has proposed a project to:

- to the extent appropriate, develop a framework and/or methods to assess and predict the potential impacts of the reduction in freshwater flows into the marine environments;
- undertake, on a national scale, a preliminary assessment on where, the reduction of freshwater and sediment inputs to marine environments is likely to have a significant impact on marine ecosystems, and;
- based on the outcomes of the above, provide guidance on future studies and/or research required to fully develop and implement such a predictive assessment capability.

The ultimate purpose is to develop a realistic and cost-effective method to assess the impact of freshwater reduction to the marine environment.

Approach and Method

The approach taken was to hold an initial workshop comprising marine specialists to try to identify where freshwater inflows to the marine environment are deemed to be important and to quantify the nature of the relationships between predominantly abiotic drivers affected by changes in freshwater inflow to the marine environment and associated response of marine ecosystems.

This initial workshop was preceded by a preliminary literature survey and followed by a detailed literature survey after the workshop and an attempted preliminary modelling investigation. The report was finalised after further scientific inputs and comment by a more limited group of workshop participants.

Conclusions of the study

The conclusions of the study are as follows:

- There is **adequate evidence that freshwater inflows to the marine environment affect marine ecosystems to a greater or lesser degree along the whole South African coastline**. The magnitude of these effects decrease on moving from the East Coast where the coastal waters are largely oligotrophic to the West Coast dominated by the upwelling of nutrient-rich seawater. It has been demonstrated that freshwater inflows significantly affect the commercial and recreational linefishery and the prawn fishery off KwaZulu-Natal, as well as spawning intensity along the KwaZulu-Natal coastline. Along the southeast, southern and West Cape coastline there are demonstrable effects on fish in the inshore habitats. The effect of submarine groundwater discharges on marine ecosystems remains uncertain and needs to be further investigated;
- The **nature of the interaction between terrestrial and marine environments differs substantially in the various coastal ecosystems of South Africa, suggesting that region-specific approaches are required** in assessing the freshwater requirements of the marine environment. It is proposed that:
  - the KwaZulu-Natal Coast behaves as one large ecosystem and should be assessed regionally;
  - the Eastern Cape Coast, extending from the Kei River to just off Port Edward and comprising a more rocky coastline with numerous small, sandy pocket beaches and many small estuaries, that is exposed to the Agulhas Current, is best assessed using a more nodal approach;

- the South Coast, from Cape Point to Algoa Bay be assessed on a coastal embayment scale, however the ecosystems further offshore are considered to be more spatially extensive;
- the West Coast with its more limited number of rivers and estuaries that are relatively remote from one another, requires that the assessment be undertaken on a node by node basis;

- While there are some studies indicating a strong interaction between terrestrial and marine environments, particularly on the East Coast, the exact nature and significance of these **relationships between freshwater-derived fluxes into the marine environment and ecosystem response is relatively poorly understood**. It is recommended that further research is undertaken as detailed below.

Recommendations

It is recommended that:

- issues around jurisdictional fragmentation and potential deficiencies in legislation be addressed;
- the extension of Resource Directed Measures (RDM) protocols to include potential freshwater requirements of the marine environment be considered. The assessment framework proposed in this report provides guidance in this regard;
- the ECO^3 concept be pursued and that techniques such as Bayesian networks to better quantify the relationships between freshwater-related changes in abiotic (and biotic) drivers and ecosystem response in the marine environment of South Africa, be assessed;
- a regional assessment of the Natal Bight and associated ecosystems be undertaken to assess the potential effects of regional changes in freshwater inflow to the marine environment. Such an assessment will require that:
  - the mouth condition, sediment and nutrient inputs of estuaries be better quantified and estimates of these fluxes be obtained for all estuaries in KwaZulu-Natal, based on the concept of a regional classification of estuaries;
  - that hydrodynamic and possibly water quality modelling of the marine environment be undertaken as part of this assessment.

In addition to the above major initiatives, it is recommended that:

- the relative importance of terrestrial and oceanic nutrient sources in nearshore and coastal shelf food webs be assessed using stable isotope analyses;
- the observed strong correlation between river flow and fish egg abundance off KwaZulu-Natal needs to be further investigated and an effort made to publish the results;

- a better understanding is obtained of the sediment dynamics in nearshore and coastal shelf waters, particularly over the Natal Bight;
- it be determined how many of the nursery area indeed perform a significant nursery function (particularly in a regional sense) in a region;
- the cueing effect be further investigated to determine its nature (*i.e.* is it olfactory or not) and importance for recruitment into estuaries;
- the concept of the surf-zone as a "cueing corridor" and the interconnectivity of estuaries due to surf-zone dynamics be further investigated;
- the potential inshore localised influence of river inputs on the West Coast (commercial gill net and beach seine fisheries) be assessed;
- a preliminary assessment of the role of groundwater in marine ecosystems be undertaken;
- a better understanding is obtained of regional coastal sediment budgets and how progressive changes in fluvial sediment discharge quantitatively affect long-term shoreline equilibria. This would include an assessment of "typical" return periods (or magnitudes) of river floods required for significant fluvial sediment inputs to the marine environment;
- the effect on South African marine ecosystems of potential changes in freshwater flow from catchments and in metocean conditions associated with climate change, be assessed.

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PART I:

A PROPOSED FRAMEWORK FOR ASSESSING THE POTENTIAL FRESHWATER REQUIREMENTS OF THE MARINE ENVIRONMENT

1. Introduction

1.1 Background

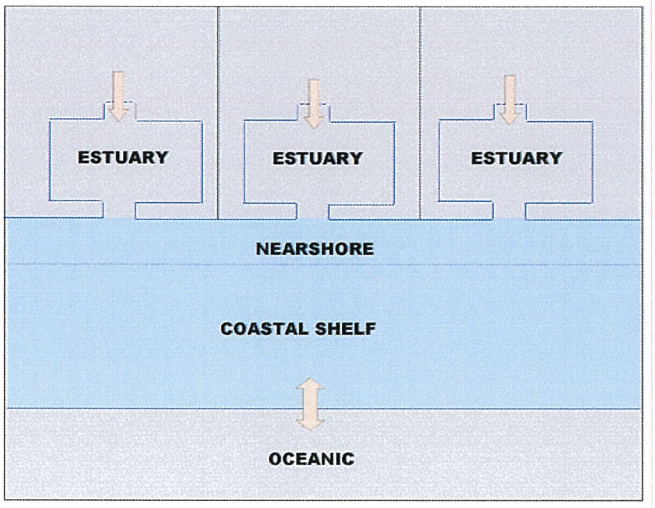
Freshwater is scarce in many regions of the world and, in this regard, South Africa is no exception. The competition for water resources, particularly those required to sustain estuarine and open coastal marine systems, relate largely to escalating conflicts between development, environmental protection and management of natural resources, the growing numbers of freshwater users and conflicts among them, and multiple authorities managing the resource. Consequently for adequately informed decisions to be made, there is a growing need to better understand the impact of altered flows of fresh water on estuarine and (coastal and shelf) marine systems[1].

It has long been recognised in South Africa that developments leading to the reduction in freshwater flows into the river/estuarine systems have a significant impact on the associated river/estuarine ecosystems. While freshwater abstraction varies greatly from estuary to estuary, in some catchments the storage capacity of reservoirs exceeds the annual runoff from rivers feeding them (*e.g.* Schlacher and Wooldridge, 1996).

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[1] In its broad sense the marine environment can be divided into four sub-domains, each with fairly distinct biophysical characteristics, namely:

- Estuaries;
- Nearshore environments;
- Coastal shelf environments ;
- Oceanic (or offshore) environment.s.



For expediency, throughout this report, references to marine ecosystems (see schematic above) is considered to include only nearshore and inner (coastal) continental shelf marine ecosystems unless stated otherwise. Specifically this definition of the marine ecosystem is intended to exclude both estuarine and deep water oceanic ecosystems.

However, only recently has there been a growing realisation and acceptance that developments leading to the reduction in freshwater flows in South African river/estuarine systems also have a potentially significant effect on open coastal marine ecosystems (*e.g.* Demetriades et al., 2000 and Louw, 2003), particularly along the east coast of southern Africa. Many species of socio-economic importance are supported by these environments and freshwater inputs may have a strong influence on their abundance.

In contrast to river, wetland, groundwater and estuarine environments where appropriate assessment frameworks and methods have been evolved to assess the potential impacts of the freshwater reduction, no similar assessment framework or method presently exists to assess the potential impacts of the reduction in freshwater flow into South African marine environments. Thus there is a need:

i) to the extent appropriate, develop a robust assessment framework and/or method to adequately assess these impacts.

ii) to undertake an assessment of the likely extent and significance of potential impacts of changes in freshwater flow and sediment discharges into South African marine environment on ecosystem functioning and integrity (and consequently local/regional economies).

1.2 Scope of Work

As a component of the Water Research Commission's (WRC) unsolicited research programme, the CSIR is to undertake an investigation that:

- on a national scale, provides **a preliminary assessment on where the reduction of freshwater and sediment inputs to marine environments is likely to have a significant impact on coastal and offshore ecosystems**. Such an assessment ideally requires that:
    - the nature of the physico-chemical and biological links between river/estuarine environments and the marine environment in the various coastal/offshore domains surrounding southern Africa be determined, and
    - based on this understanding of the links between the physico-chemical and ecological systems, quantify and predict wherever possible the extent and significance of the potential impacts of changes in freshwater flows and sediments discharges on the functioning and integrity of marine ecosystems.
- to the extent appropriate, **provides a framework and/or suggest methods to assess and predict the potential impacts of the reduction in freshwater flows into the marine environments**. Recognising the likelihood of ongoing financial constraints in making such assessments, the CSIR is to attempt to develop and test the efficacy of a low-cost, predictive capability to be used in a "rapid/intermediate-type" Reserve Determination assessment (see Part II: Section 2);

- provides **guidance on future studies and/or research required to fully develop and implement such a predictive assessment capability**, i.e. provide the Water Research Commission with guidance on the nature and extent of the studies and/or research required to ensure that the potential impacts of the reduction in freshwater flows into the marine environments are adequately assessed when considering the desirability of proposed developments potentially resulting in such a reduction of freshwater inflow.

The ultimate goal is to develop a **realistic** and **cost-effective** method to assess the impact of freshwater reduction to the marine environment without resorting to extensive studies, as funding for such studies is unlikely to be forthcoming for each system being assessed. The extent to which this is possible is not certain, however it is assumed that through judicious measurement, monitoring and focussed research, it should be possible to make ongoing improvements in the confidence of such assessments without dramatically increasing the costs associated with each and every estuarine system assessed for its freshwater requirements using the existing methods, i.e. it is assumed that the Reserve Determination Methods assessments (DWAF, 2004) can be extended to include the freshwater requirements of the marine environment without excessively increasing the costs of the overall assessment.

1.3 Approach and Method

The approach initially proposed was first to decide on an appropriate preliminary assessment framework/method to assess the potential freshwater requirements of the marine environment of South Africa and then utilise this approach in an initial workshop of experts that would:

- collate ideas around the ***likely nature of the physico-chemical and ecological links between river/estuarine environments and the marine environment in the various coastal/offshore domains surrounding southern Africa that are most likely to be impacted upon by changes in freshwater inflows (and associated nutrient and sediment fluxes) to the marine environment;***
- determine the ***temporal and spatial scales (temporal and spatial resolution, duration and extent) of measurements or modelled time series required to ensure a sufficiently robust assessment*** of the potential impacts of a reduction of freshwater on marine ecosystems.

After this initial workshop, the CSIR was to endeavour to characterise the abiotic (and biotic) drivers according to the temporal and spatial scales (temporal and spatial resolution, duration and extent) of relevance as identified in the initial workshop, using existing measured data and numerical modelling of marine hydrodynamics and water quality. Limited data availability and budget constraints for this component of the project suggested a more restricted approach comprising conceptual modelling only to the extent required to inform a basic understanding of potential mechanisms/vectors of impacts in the marine environment as required for the a proposed second and final workshop where the goal was to:

- determine the potential efficacy of the predictive capability provided by the added temporal and spatial information generated by a limited modelling effort, data collated during this interim period and/or the interpretation of previous modelling results (where available);
- complete a preliminary assessment of the freshwater requirements of the marine environment of South Africa.
- obtain expert opinions on the nature and extent of the field work, measurement programs, studies and/or research required to ensure that the potential impacts of the reduction in freshwater flows into the marine environments are adequately assessed when considering the desirability of proposed developments leading to the reduction of freshwater inflows to marine environments.

The two workshops, while relying heavily on the collective scientific expertise of the group, were to focus on developing an assessment framework and management issues.

It was planned after the final workshop to produce a report that summarised the outcomes of the project and that provided ***recommendations on the nature and extent of the studies and/or research required*** to ensure that in future that the potential impacts of the reduction in freshwater flows into the marine environments are adequately assessed.

After the initial workshop it became clear that there remained many more unresolved issues than originally anticipated (see Appendix C) and that no clear framework existed to guide the scientific assessment of the potential freshwater requirements of southern African marine ecosystems. The approach to the project was revised accordingly.

Instead of holding a second large and costly workshop where contact time between the various participants inherently would be limited, it was decided to:

- focus on developing an appropriate framework within which the outcomes from the initial workshop and subsequent specialist feedbacks could be utilised to assess the importance of the role of freshwater and associated fluxes in South African marine ecosystems;
- distribute the summary of the initial workshop in a draft report to selected members of the original project team for review and to obtain more focussed inputs to the final assessment and recommendations on the nature and extent of the studies and/or research required to better assess the freshwater requirements of marine environments. An added advantage to this approach was that the engagement of a smaller, more focussed group of specialists allowed for easier scheduling of the inputs to the project, an issue that proved particularly problematic for the first workshop.

1.4 Structure of the Report

The report is structured as two separate parts:

- **Part I,** that introduces the study and proposes an appropriate framework for:
  - undertaking an initial assessment of the role of freshwater inflows and associated fluxes in coastal and shelf marine ecosystems of South Africa, and ;
  - managing the potential effects of changes in these fluxes into marine ecosystems;

- **Part II,** comprising an initial assessment of the role of freshwater in South African marine ecosystems. This section also provides guidance on the nature and extent of the studies and/or research required to ensure that the potential impacts of the reduction in freshwater flows into the marine environments are adequately assessed when considering the desirability of proposed developments potentially resulting in a reduction of freshwater inflow into estuarine and marine ecosystems.

2. Literature Review

Here we review progress in developing assessment and management frameworks that take adequate cognisance of the freshwater requirements of marine ecosystems. Based on this review, a summary is provided of the issues that need to be considered when developing such an assessment and management framework. The approach and method adopted for this study take into consideration all of these issues and, in particular, is guided by:

- existing and ongoing studies (both local and global) that attempt to:
  - determine the **nature of the primary physico-chemical and ecological links** between river/estuarine environments and the coastal/offshore environment in various coastal/offshore domains;
  - predict the **extent and significance of the potential impacts of changes in freshwater flows** and associated nutrient and sediments fluxes into the marine environment on ecosystem functioning and integrity, and consequently the effects on local/regional economies that are based on the "ecosystem goods and services" supported by these marine environments;
  - set-up an **appropriate assessment and management framework** for managing marine environments, particularly in terms of their freshwater requirements.
- the **requirements of the National Water Act** (Act 36 of 1998) and other relevant legislation;
- existing **methods to assess the potential impacts of the freshwater reduction in South African river, wetland, groundwater and estuarine environments**, *e.g.* the Resource Directed Measures reported in DWAF (2004). These are discussed in greater detail in Part II: Section 2 of this report;

- the expectation that there are likely to be **severe limitations in the resources available to assess the potential impacts of the freshwater reduction** in both southern and South African marine environments.

2.1 International

Numerous qualitative and semi-quantitative studies (and a more limited number of truly quantitative studies), have been undertaken for the management of estuarine environments in terms of their freshwater requirements. However, similar studies of the freshwater requirements of the marine ecosystems are less numerous.

It is not the intention here to extensively review and summarise the findings of these studies. Rather the intention here is to extract from these studies those common elements, particularly the approach and methods used in making the various assessments that are relevant to developing an assessment and management framework to inform decisions on developments that may significantly change the freshwater inflows to these ecosystems.

While a number of international studies have been undertaken attempting to describe and assess the role freshwater in marine ecosystems (*e.g.* Robins *et al.*, 2005), only a limited number of reviews of such studies exist. In terms of relevance to southern and South African marine ecosystems, the most pertinent is the review undertaken by Gillanders and Kingsford (2002) that provides an extensive overview of the impacts of changes in freshwater flows to marine environments (including estuaries). Their review is focussed primarily on Australian systems but also includes a number of southern African studies (*e.g.* Schlacher and Wooldridge, 1996; Quinn *et al.*, 1999). Specifically, they:

i) make a number of observations on perceptions around the issue of freshwater requirements of marine ecosystems;

ii) describe the nature of possible functional linkages associated with freshwater flows between catchments and marine ecosystems' and;

iii) make recommendations on appropriate approaches to the assessment and management of open coastal marine systems in terms of their freshwater inflow requirements.

The focus of their review on Australian systems makes it particularly pertinent to the assessment of South African coastal ecosystems due to the many similarities between Australian estuarine systems and those found in South Africa. Similar to most Australian sub-tropical and temperate coastal ecosystems, much of the South African coastline is characterised by many smaller temporary open and closed estuaries, rather than a limited number of large river systems with strong freshwater inflows, as is often the case in the generally better studied European systems and many tropical systems. In systems comprising many smaller estuaries, the nature of the functional linkages between the catchment and marine ecosystems is often subtle, highly complex and in most cases not as simple as being predominantly related to large nutrient and sediment

fluxes into the marine environment due to major river inflows (as is typically observed for most tropical and many European systems).

Gillanders and Kingsford (2002) provide an excellent overview of many of the issues surrounding the management of estuaries, coastal and offshore environments in terms of changes in the nature and quantity of freshwater inflows to these environments. They, amongst others, make the following observations pertinent to developing a structured approach to assessing the extent of freshwater dependency of South African coastal marine ecosystems and the potential requirements of such an assessment and management framework:

- **Over exploitation of water is fast becoming one of the worst environmental legacies of future generations.** This is particularly true of the typically water-scarce countries of southern Africa;
- **Globally, there is a strong perception that "water going to sea is wasted"**, a perception that is likely to prevail in a South African context, particularly amongst the users of freshwater resources in the river catchments. This perception exists despite both strong global (*e.g.* Gillanders and Kingsford, 2002) and local (*e.g.* Louw, 2003) evidence to the contrary. **Most water users are only interested in looking at upstream practices impacting their access to water or its quality and rarely look "downstream". Consequently, rarely are the ecological needs of marine environments considered when allocating freshwater resources.** This has largely been true in southern and South Africa (DWAF, 2004), however a number of recent studies indicate an encouraging change in this *status quo* (*e.g.* Louw, 2003; Monteiro and Matthews, 2003);
- Where impact assessments of the reduction of freshwater inflows into the marine environment have been undertaken, **typically, there is a lack of interest in following up major projects after they have been completed.** Such follow-ups provide major opportunities for verification of hypotheses related to the predicted potential impacts associated with changes in freshwater flow to the marine environment. The lack of follow–up on environment impact assessments in general, has been articulated as a particular concern by the South African scientific community and environmental impact assessment practitioners;
- **Downstream areas are often out of the jurisdiction of the agency responsible for the upstream water development project.** This is a particular concern in South Africa where the Department of Water Affairs (DWAF) is largely responsible for managing upstream activities while the Department of Environment Affairs and Tourism (DEAT) is the dominant role-player in managing marine ecosystems (*i.e.* the downstream activities);
- In addition to the regulatory jurisdiction being fragmented, there **often exist deficiencies in the existing regulatory environments that complicate any attempts to manage holistically the issues surrounding changes in freshwater flow to the marine environment** (see Part II, Section 2 and Appendix A). Of specific concern is the

South African National Water Act 36 of 1998, that provides for the integration of water resource management and co-operative governance via the National Water Resources Strategy that sets a framework for water resource management, **but does not define the marine environment as a water resource and therefore presently provides limited if any protection to the marine environment in terms of water resource utilization and allocation (*i.e.* changes in freshwater inflows and related fluxes from adjacent catchments).**

- **The jurisdictional fragmentation referred to above may be further compounded by the fact that in many cases the management of water resources are or should be a transboundary endeavour** (*i.e.* the river/water resource being managed may extend across a number of countries and be subject to management by the water agencies of more than one country). However, recent projects such as the European Union co-funded Catchment2Coast project that assesses the linkages between Maputo Bay and upstream catchments (Monteiro and Matthews, 2003), provides a good example of efforts to ensure transboundary collaborative research and transboundary management of water resources.

- **The assessment of "downstream" impacts (i.e. in this case on marine ecosystems) is typically a highly complex and very expensive process**. A typical constraint to applying quantitative (and all but the most basic qualitative) methods, is the inherent lack of understanding of the natural functioning of the complex ecosystems under consideration. Furthermore the required monitoring data to make even the most basic assessments are either not available or are of too short a duration to allow robust predictions. **Most quantitative methods require a fairly robust understanding of the functioning of the ecosystem(s) of relevance, before it becomes possible to predict potential impacts or changes to the ecosystem due to changes in freshwater flows into that environment.**

- **The assessment and management frameworks developed need to have a clear idea of the environmental objectives to be achieved** (that typically would require consideration of existing as well as potential future ecosystem services supported by these environments)**, as well as the means** (management and monitoring/measurement programs) **to ensure that these environmental objectives are achieved.** For example, management on the basis of indicator, flagship, umbrella or endangered species requires that the species identified indeed are an appropriate measure of the environmental objectives for the ecosystem under consideration.

- **To simplify the assessment and management approach it is often necessary to identify one or more "keystone"[2] or indicator species.** The chosen keystone or indicator species will depend both on management objectives as well as the role played by the species in ecosystem functioning. The choice of one or more keystone or indicator

[2] Care should be taken in identifying or using the concept of keystone species as the definition of *keystone species* remains controversial (Davic, 2003).

species to assess and manage is perhaps the most critical decision that has to be made in any such assessment.

- **The boundaries of marine ecosystems (potentially affected by changes in freshwater inflows and associated fluxes) are not easily defined because physical conditions and the movement of organisms (e.g. a pelagic life history stage followed by post-settlement movement to other habitats), as well as their prey, fluctuate over large distances in the sea.** This greatly complicates the assessment of potential impacts on marine environments due to changes in freshwater inflow.

- **Where studies have been undertaken, they mostly comprised small-scale studies that do not truly encompass the full extent (geographic and ecosystem functioning) of the environment that is likely to be impacted upon.** Whilst these smaller scale studies are useful in characterizing the impacts for a single species or perhaps a number of species, they provide little guidance to managers who need to take a more holistic ecosystem view. Until recently most studies in South Africa comprised such small to medium scale investigations, however there is now a greater appreciation for the need for more regional studies of potential ecosystem impacts in marine environments (*e.g.* Louw, 2003) and assessment methods to deal with ecosystem complexity (Peters *et al.*, 2007).

- **Studies investigating the impacts of increased freshwater flows are typically more common than those for a reduction in freshwater inflows.** The reason for this is that increases in freshwater inflows are characteristically related to "events" such as flooding. The consequences of these events are typically discernable over a short period of time and can clearly be linked to the "event". In contrast, impacts related to the reduction of freshwater inflows are generally more subtle and occur over a much longer time period. The implication of this is that **much longer records or measurements time series are required to assess potential impacts due to the reduction of freshwater inflows than would be the case for assessing the potential impacts due to increased freshwater inflows**. This is particularly true for the higher trophic levels that have longer life cycles. Added complexities are:
    - that the impacts related to changes in freshwater inflows are rarely symmetrical, *i.e.* the impact of an increase in freshwater inflow, is rarely simply similar in magnitude and opposite to that due to a similar decrease in freshwater inflow.
    - the longer and more complex the life-cycle of the species under consideration, the greater the influence of environmental factors other than those directly related to changes in freshwater flows to the marine environment on the species being assessed. This results in a requirement for a more extensive knowledge of these other factors and their impact on species health and abundance, to be able to discern which impacts are primarily due to the reduction of freshwater inflows to the marine environment. This is particularly true of fisheries species, the exploitation of which often provide the only source of health and/or abundance

data with which to assess the influence of changing freshwater inflows into coastal ecosystems.

Any assessment and/or management framework developed will need to resolve the above issues as best possible. In the international literature, recommendations in this regard include the following:

- Given the uncertainty in predicting the ecological effects of water management strategies/activities or the efficacy of measures aimed at regulating them, an **active or adaptive rather than a passive management strategy** *(e.g.* Gillanders and Kingsford, 2002) should be adopted. Most literature on resource management assumes *a passive strategy* whereby there is a choice of one policy as being optimal (Walters and Holling, 1990), historical data are used to provide a best estimate of the potential ecological response and the management decisions assume that the predictive model used is correct. Based on such an approach, highly quantitative optimisation methods may be used to decide upon the best strategy (*e.g.* Li and Mays, 2000). Such an approach, although more easily implementable, is vulnerable to inaccuracies in the predictive model(s) used (*e.g.* see Pilkey and Pilkey, 2007). An **active or adaptive strategy therefore is expected to be more effective**. In such a strategy, available data are used to suggest a range of alternative response models. Based on the plausibility or probability of one or more of these models being correct, an appropriate management policy is selected, *i.e.* a Bayesian-type approach is used rather than standard frequentist statistical methods. A Bayesian network, besides being able handle a high degree of complexity of systems, has the further advantage of being able to explicitly handle and quantify the uncertainties in any predictions (*e.g.* Peters *et al.*, 2007), a critical component in assessing the risks associated with any particular decision. However, due to the potentially changing nature of a policy based on an active or adaptive strategy, it is likely to be much more difficult to implement.[3]

- To ensure robustness, it is recommended that **assessments and management approaches should include both habitat-forming species as well as organisms within these habitats.** For example, Gillanders and Kingsford (2002) endorse a measurement/monitoring and management approach that focuses on habitat forming organisms as well as the ecologically (*e.g.* keystone species) and socio-economically relevant organisms (*e.g.* fisheries species) that are associated with them. However due to the costs of field measurements and monitoring, managers often are forced to use a simplified management approach using the status of indicator, flagship, umbrella or

[3] Typically, for there to be an acceptance of policy, legislation and associated management activities by affected parties, the policy and management outcomes (both present and future) need to be clearly understood (*i.e.* both individuals and commercial operations require a degree of certainty as to the potential consequences of policy and legislation on their operations). Consequently there is likely to be a resistance to the implementation of adaptive strategies due to the uncertainty of outcomes associated with both existing and future implementations of such an adaptive policy.

endangered species as a metric for assessment studies and management. Management approaches therefore may include:

- a narrow management approach focussed on the maintenance of a particular fishery (*e.g.* single species fishery management);
- an ecosystem management approach[4] aimed at the maintenance of ecological processes and ecosystem function
- a management approach focussed on both the maintenance of ecological processes and ecosystem function, as well as the maintenance of biodiversity and the protection of rare and endangered species.

Gillanders and Kingsford (2002) suggest that the most effective approach to management is the concept of *keystone species* as suggested by Simberloff (1998). A keystone species approach focuses on understanding the mechanisms that underlie the structure and function of ecosystems (see Appendix B) and thus has the potential to combine the attractive features of single species management and ecosystem management approaches.

- In the absence of appropriate assessment frameworks/methods and an adequate understanding of the impacts of the many developments (proposed or underway) that affect freshwater inputs in marine systems, ***the best management approach is to attempt to mimic the natural flow regime as far as possible*** to provide an acceptable median flow (base flow) and well defined pulse (flood) events. Both types of flow (base flow and flood events) are important as both play a significant role in maintaining the physical environment and sustaining the habitat-forming species and the organisms associated with these habitats.

- ***To ensure robust prediction of potential impacts in the future, full advantage needs to be taken of all opportunities to understand and assess the predicted impacts of changes of freshwater flows into estuarine, marine environments.*** One particular such opportunity would be to undertake extensive monitoring and modelling activities downstream of a newly constructed dam (*e.g.* the proposed Skuifraam Dam on the Berg River). In the process of being filled the dam will result in a major decrease in freshwater flows (and consequently nutrients) and sediment transport to the downstream estuarine, marine environments. The impacts of this major reduction in freshwater flow could then be assessed. Similarly, serious drought conditions could provide opportunities to assess the impacts of a decrease in freshwater flows to marine environments[5]. This approach was taken in the Thukela study (Louw, 2003). Thus, it is important that the regulatory and management agencies are made aware of these opportunities to assess the impact of changes/reduction in freshwater flow to downstream environments (i.e. marine ecosystems) and that they respond appropriately.

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4 Ecosystem management that focuses on the maintenance of ecological processes and ecosystem function, may be deemed inappropriate by some (*e.g.* by conservationists) in that many ecosystem processes may be maintained even as species disappear. Certainly an ecosystem management approach alone is unlikely to be adequate, should the maintenance of biodiversity be considered to be of prime importance.

5 One should be cautious in extrapolating studies of such a nature as developments such as dams on a river may not result in the same changes in flows, nutrient fluxes and sediments transports as occur during periods of drought.

- Numerical modelling can play a significant role in improving assessments. In the absence of adequate environmental monitoring data, numerical models have the ability to characterise the physico-chemical environment with sufficient detail and accuracy to provide the basis for better predictions of potential ecological responses to changes of freshwater inflow to marine environments[6]. Fairly extensive use has been made of numerical modelling in assessing the potential impacts of the reduction in freshwater inflows to estuarine systems, particularly where there is a complex response to such freshwater inflows to an estuary (*e.g.* Bate and Adams, 2000; van Ballegooyen *et al.*, 2004).

2.2 Southern Africa

Until recently most studies in South Africa comprised small to medium scale investigations (*e.g.* Whitfield, 1994; Harris and Cyrus, 2000; Harris *et al.*, 1995, 2001; Strydom *et al.*, 2002, 2003, Strydom and d'Hotman, 2005), however more recently there has been an appreciation for the need for more regional studies of potential ecosystem impacts of the reduction of freshwater inflows to marine environments (*e.g.*, Louw, 2003, Lamberth, 2003; Demetriades *et al.*, 2005; Lamberth and Drapeau, 2007). The two most notable assessments of the impacts of changes in freshwater inflows to the marine environments of relevance here are:

- the recent Reserve Determination Study for the Thukela catchment that was extended to include the potential impacts of freshwater reduction on the adjacent marine environment (Louw, 2003), and;
- the Catchment2Coast Project undertaken in Maputo Bay and its associated catchments (Monteiro and Matthews, 2003).

Both of these projects, their approach and their relative strengths and weaknesses are discussed below.

In addition to the above studies, a significant initiative of relevance is the ECO^3 research project presently being executed under the leadership of the CSIR. It is an initiative that intends to provide a robust and flexible framework, based on a Bayesian network approach, for providing a holistic assessment of ecosystem and economic (and social) imperatives when considering potential future developments that will either indirectly or directly affect the exploitation of natural resources (Peters *et al.*, 2007). The main case study in this project has been coupled catchment-coastal model of the Inkomati Catchment and its impact on Maputo Bay in Mozambique (IncoMaputo Model). The first model (IncoMaputo I) was first built at a coarse catchment scale and aggregated catchment activities both spatially and temporally. The second model (IncoMaputo II) links the highveld, escarpment and lowveld regions of each basin in the catchment in a spatio-temporal model which links upstream activities to downstream impacts within the catchment explicitly.

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[6] A numerical modelling approach is core to the Catchment2Coast project focussed on Maputo Bay and its surrounds (http://www.catchment2coast.org; INCO, 2003). However, depending on the level of sophistication of the modelling effort, this may be quite costly and require a large amount of project resources.

2.2.1 *Thukela Study*

The purpose of this study was to assess the economic implications of changes in fisheries catches due to potential changes in the flow regime of the Thukela River as a result of upstream developments. The specific objectives of the study were to:

- assess the economic implications of various flow scenarios in the Thukela River;
- determine whether there is a link between flow and catch in the relevant fisheries (assuming that a nutrient and sediment function is being provided by freshwater flows);
- define the link if it does exist;
- isolate the contribution of the Thukela flows to coastal and shelf ecosystems.

The two fisheries considered in this study were the prawn and recreational and commercial boat-based line fisheries of KwaZulu Natal. Both involve species of socio-economic importance, rather than keystone species in the more classic sense of being indicator or umbrella organisms representing of ecosystem health and functioning and/or biodiversity. Given the disparity in the complexity of the relationships to be considered, the approach to assessing the impacts of changes in freshwater flows on the two fisheries differed substantially. The prawn fishery assessment needed to only consider the relatively short life-cycle of prawns while the line fisheries assessment needed to consider the more complex and longer life-cycles of a number of fish species.

The prawn catch was modeled as a function of an environmental index that was a linear combination of:

- A ***nursery index*** that is the sum of a recruitment index and emigration index based on river or estuarine flows during critical periods of recruitment and emigration from the estuary. (The recruitment index characterizes the period when the prawns in the postlarval stage enter the estuaries, where they mature to the juvenile stage whereupon they return to the Thukela Bank, *i.e.* emigrate to the marine environment).
- A ***nutrient index*** based on a nutrient index for the larval stage comprising mostly dissolved nutrients that support the growth of phytoplankton that are a major component of the diets of the planktonic larval prawns and a nutrient index for the adult stage comprising available organic carbon as food for sub-adult and adult prawns that is derived from both indirect inputs to the marine food chain (*i.e.* beginning with phytoplankton production) to direct inputs via organic and detrital input from river flow.

The relative weighting of the various indices were varied to obtain the best relationship between prawn catch and the overall environmental index. The relationship developed was a log relationship that explained 77% of the variance of the prawn catch data in terms of the overall environmental index. Based on this predictive relationship the potential impacts associated with possible future flow scenarios of the Thukela River were assessed. It should be noted that the compilation or calculation of the overall environmental index was somewhat of a subjective

process, in that the weighting used to compile the index was iteratively optimized to find the best fit, and that the predictive capability relies on the fact that the established relationship between prawn catches and the calculated environmental index is assumed to be stationary in a statistical sense. This may not be a valid assumption.

The assessment of the impacts of the reduction of freshwater inflows to the marine environment on the recreational line fishery was more exploratory in nature due to the complexity of the relationship between fish catch and effort data and freshwater inflows to the marine environment. Exploratory analyses were undertaken using Spectral Analysis and General Linear Models. With the exception of the King Mackerel, the strongest relationships between catch per unit effort (CPUE) and freshwater inflow to the marine environment were with reef species that show a high degree of residency. The freshwater flow typically explained between 12% and 67% of the variability in CPUE. In this analysis the freshwater flow is considered a proxy for many drivers. In developing the above predictive relationship it is merely being stated that freshwater flow or any co-varying variable such a rainfall, nutrient inputs to the marine environment, *etc.* explain between 12% and 67% of the CPUE of the various fish species. Furthermore, the limitations of using CPUE as a proxy for abundance or catch should be recognized (*i.e.* CPUE may be a biased measure due to freshwater flow related behavioral changes, *e.g.* fish may respond to increased water column turbidity by aggregation that results in an increase in their catchability).

Based on these relationships, the changes in catch related to various flow scenarios were predicted and the economic implications of these changes estimated. Seemingly the economic impacts associated with changes in catches due to the presently proposed reduction in freshwater inputs to the marine environment from the Thukela River are not likely to be significant in the short term, however future worst case development scenarios suggest that the impacts may be appreciable. A more recent publication by Lamberth and Drapeau (2007) explores in greater detail the relationship between freshwater flow and the catch of recreational line fishery species.

Both of these analyses remain somewhat deficient in terms of providing a predictive capability and neither explicitly consider specific abiotic (or biotic) drivers but rather freshwater inflow to the marine environment as a proxy for various drivers such as nutrient and sediment fluxes. In general, correlation or regression analysis to identify environmental variables contributing to variation in fisheries catches can be criticised for a number of reasons. These are discussed in Section 4.5.6 below.

2.2.2 *The Catchment2Coast Project*

Catchment2Coast was an international and multidisciplinary ecosystem scale research project that aimed to understand the linkages that govern the economic dependency of tropical coastal resources on their associated river catchments (Monteiro and Matthews, 2003; Marchand, 2003), *i.e.* the linkages between human activity in river catchments, such as farming, irrigation and water abstraction, and its impact on coastal resources. The focus in this project was on the Maputo Bay

ecosystem and shrimp industry, which provides important livelihoods to a large number of fishers and their families. (The Maputo Bay shrimp fisheries are estimated to be worth some three million US Dollars annually and, albeit showing strong inter-annual fluctuations usually attributed to environmental factors, they provide livelihoods to more than 2 000 fishers and their families.)

The project was transboundary in nature in that it involved three catchments (Inkomati, Umbelúzi and Maputo) extending over three countries (Mozambique, South Africa and Swaziland). The collaborative research effort in the Catchment2Coast project was co-funded by the Fifth Framework Programme of the European Union and the nine partners involved, which are scientific institutions, three from Europe and six from South Africa, Swaziland and Mozambique. The overall cost of the project, including funding in kind from the partners, is estimated to have been approximately 2.5 million Euros.

The core hypothesis of this project was that the most important biophysical interactions between freshwater catchments and coastal domains occurred at the sub-seasonal event scale (days). Unless these scales were resolved the assessment of the economic consequences of those interactions would not be sensitive, adequate or robust. To achieve this, an explicit dynamical capability was required. This project used a number of numerical models (coastal, river basin and ground water), with the required dynamical capability, in order to implement a system scale approach to the functional dependence of coastal systems on river basin drivers. The shrimp (*Paeneus indicus*) was used as an indicator of the ecosystem productivity response to catchment forcing. This was a necessary simplification because the focus of the project was on the system linkages rather than coastal food web complexity. Secondly, shrimp Catch Per Unit Effort (CPUE) was the best long term proxy data for coastal ecosystem productivity.

The scientific focus of the biophysical part of the project was guided by a number of hypotheses, related to scales of both physical and biogeochemical forcing that also are likely to be of relevance to the South African coastline. Of particular relevance to the assessment of the impacts of the reduction of freshwater flows to South African marine environments was the explicit consideration in the Catchment2Coast project of temporal and spatial scales of relevance in linking the models in the various domains as well as the specific input data requirements to the models in the various domains, *i.e.* the requirements associated with the simulation and linking of river catchment models, groundwater models, estuarine, coastal (including mangroves) and offshore hydrodynamic and water quality models, a mangrove model and a resource economy model. The most significant decision in linking the various models was that:

- the temporal resolution of the models had been maintained that enables explicit simulation of event-scale processes, and;
- that the spatial resolution had been reduced by aggregating data into a limited number of spatial domains (river, estuarine/mangrove, bay, offshore, *etc.*).

Consequently the methods, techniques and understanding (particular of the temporal and spatial scales of aggregation and the effective linking of drivers to ecological response models) obtained during the Catchment2Coast project are expected to be key to future assessments of the reduction of freshwater inflows to the South African marine environment.

A similar approach is indicated for the preliminary assessment of the potential impacts of freshwater reduction on the marine environment of South Africa. Potential sub-domains to be considered include the surf-zone, coastal embayments (*e.g.* Algoa Bay, St Helena Bay), protected shelf regions (*e.g.* Natal Bight) and the offshore domain.

While this project focused on a single but economically important coastal living resource, the shrimp, it methods developed should be generic enough to deal with other recognized impacts such as mining effluents, pathogens, eutrophication, erosion and silting. A particular strength of the project was that it integrated biophysical and resource economics models to translate the impacts into urban and rural livelihoods. (See www.catchment2coast.org for more details on the project.)

3. Required attributes for an assessment and management framework for South African marine ecosystems

The required attributes of an assessment and management framework for South African marine ecosystems in terms of their freshwater flow requirements are described below. These requirements have been developed based on the initial workshop undertaken during this study (Section 3.1) followed by a comprehensive review of existing literature on this subject and a summary these requirements (Section 3.2).

3.1 Initial Assessment Workshop

A preliminary assessment of the potential impacts of freshwater reduction on the marine environment of South Africa was undertaken by holding an initial workshop followed by a series of discussions with workshop participants and finally a formal review and selected further contributions to the report by a more limited number of the workshop participants.

The purpose of the initial workshop was to attempt:

- **to collate ideas around the nature of the physico-chemical and ecological links between river/estuarine environments and the coastal/offshore environment in the various coastal/offshore domains surrounding southern Africa** most likely to be impacted upon by changes in freshwater, nutrient and sediment inflows to the marine environment;

- to attempt to **develop hypotheses** that describe the processes (drivers) and associated ecological responses. Some of the hypotheses developed are generally accepted, others are more speculative;
- **to determine the temporal and spatial scales (temporal and spatial resolution, duration and extent) of the measurements or modelled times series required to ensure a sufficiently robust assessment of the potential impacts of a reduction of freshwater on marine ecosystems.** The workshop participants were asked the exact nature of the data and information that would be required to confirm and quantify the hypothesised ecological responses.

The intention then was to collate, if possible, all information, data and modelling results of relevance (and to supplement the model results where appropriate) before holding a final workshop. The purpose of this final workshop was to **select appropriate measures, methods and predictive strategies for testing any hypotheses developed** and **to assess the potential impacts of the reduction of freshwater inflows to marine environments,** based on all available data and information.

For a number of reasons, this process was not completed during the initial workshop (see Appendix C). Consequently, after the initial workshop it was decided rather to hold a series of discussions with workshop participants, obtain selected further contributions to the report by a limited number of the participants in the initial workshop and summarise the findings in a report that would be formally reviewed.

Unfortunately, due to time constraints not all regions could be assessed during the initial workshop. It was therefore decided to focus on the KwaZulu-Natal and the West Coast regions of South Africa as it was felt that this would provide two contrasting extremes of the assessment. Consequently detailed assessments were only undertaken for these two regions during the initial workshop.

The assessment in the initial workshop was based on a driver-response model that essentially comprises a "bottom up" approach where the starting point was to list all potential drivers (of ecological responses) that are susceptible to changes due to changes in freshwater flows and then to assess the ecological response to these drivers. This approach presented a number of issues that needed to be resolved, some due to the adoption of a driver-response model with broad ecological categories and others that are simply inherent to such an assessment (see Appendix C). These included:

- the difficulty in deciding upon a **spatial domain of interest,** *i.e.* dimensions of the ecosystem to be assessed;
- the difficulty in deciding upon **one or more keystone species** relevant to the region of interest;

- the realisation that the **choice of a spatial domain (*i.e.* spatial extent of the relevant ecosystem) and one or more keystone species was an iterative process;**
- a **lack of knowledge of some of the drivers and ecological response(s)** to changes in these drivers;
- **a lack of critical measurements required to adequately characterise the abiotic and biotic drivers** of relevance;
- **the uncertainty amongst workshop participants as to what constituted abiotic (or biotic) drivers** (*e.g.* loads of dissolved nutrients and particulate organic matter into the marine environment, *etc.*) and **the factors that merely determine or can be used to characterise the spatial and temporal changes in the identified drivers** (*e.g.* freshwater flows, state of an estuary mouth, *etc.*).

Most of the above issues were resolved (either at the workshop or shortly thereafter), however two specific issues require further discussion, namely:

- the realisation during the workshop that the **various marine ecosystems (biogeographic domains) along the South African coastline are fundamentally different and require different methods of assessment** (*e.g.* the KwaZulu-Natal coastline requires a regional assessment while the assessments along the West Coast are more likely to be nodal).
- the realisation that **the driver-response approach taken using broad ecological categories was flawed in that the ecological categories selected were too broad to be meaningful in all cases.** In some cases the behaviour or responses within the various categories proved to be inconsistent (*i.e.* the response of various species within the same broad classification to a specific driver may be significantly different).

These issues are dealt with in greater detail in the detailed assessments reported in Part II of this report.

3.2 Summary of Required Attributes

Based on the learning from the initial workshop and a literature review, an assessment and management framework that takes cognisance of the freshwater requirements of the marine environment, needs to:

- **Have clearly defined and agreed upon goals and environmental objectives.** While the specific environmental objectives may vary from region to region, it is expected that the assessment and management framework to be used nationally would need to have specific goals in mind and comprise a consistent philosophy in terms of the broad environmental objectives of relevance[7]. For example, the management approach and

[7] Presently an initiative is underway within a CSIR-led research consortium to provide a framework (ECO^3) that assesses the outcomes of various development options in terms of maximising the total economic value

measures used to maximize the exploitable living marine resources in an ecosystem are unlikely to be same as those designed to safeguard biodiversity[8];

- **To resolve the issues of jurisdictional fragmentation and deficiencies in legislation.** The potential transboundary nature of the ecosystems being assessed and managed (*e.g.* migratory fish stocks) implies a degree of co-operation between countries in managing water resources. In addition, cognisance needs to be taken of international treaties and agreements (*e.g.* biodiversity, *etc.*) of relevance to South Africa. There exist jurisdictional fragmentation and deficiencies in South African legislation that are of concern (see Part II: Section 2). These are issues that cannot be addressed in this study, however are nevertheless issues that need to be highlighted and considered when developing an appropriate assessment and management framework;
- **Be able to provide sufficiently robust assessments of the importance of freshwater inflows to marine systems to be able to effectively motivate, where necessary, for an ecological reserve (of freshwater flow) for marine environments.** In particular, the assessment methods need to be sufficiently quantitative and robust to counter the perception that "water going to sea is wasted". Ultimately these assessment methods need to be legally defensible, primarily by being scientifically defensible. There needs to be a **clear analysis and management of uncertainty** in the assessment and management framework for managing marine environments in terms of their freshwater requirements. If the uncertainties in the predicted impacts of changes in freshwater flows to the marine ecosystems are not adequately quantified and managed, this is likely to lead to:
    - the endorsement of the precautionary principle which has the potential to be overly restrictive in the allocation of freshwater resources for purposes other than the maintenance of ecosystems resulting in unacceptably high "opportunity costs" in terms of potential development, and/or
    - the rejection of the assessment outcomes by potentially impacted upstream water users and result in a dispute over associated management activities,

  neither of which is an optimal outcome.
- **To be simple and inexpensive yet sufficiently robust and quantitative to provide the necessary management advice.** Due to the complexity of the ecosystems being assessed and the limited time and resources typically available to make such assessments, a particular effort is required in this regard. Issues that need to be considered are:

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of goods and services from the natural environment (Peters *et al.*, 2007), however there is recognition that presently issues such as cultural values and maintenance of biodiversity are dealt with poorly (or not at all) by such a framework due to a lack of quantitative measures of cultural and biodiversity issues in terms of economic value. Antrobus and Law (2005) have described the many issues around the economic evaluation of biodiversity, however their focus was only on the freshwater ecosystems of South Africa.

8 In general biodiversity issues are poorly dealt with in existing assessment and management frameworks due to the perceived inadequacy of available metrics.

- The need for the biogeographic domain (*i.e.* appropriate ecosystem extent) of the assessment to be **sufficiently extensive** to encompass the full extent (geographic and ecosystem functioning) of the environment that could be impacted upon (*i.e.* a decision needs to be made as to the dimensions of the ecosystem under assessment);

- The need to simplify the assessment by either by:
  i) concentrating on **indicator, flagship, umbrella or endangered species**, or;
  ii) adopting an **ecosystem management approach** focussing on physico-chemical and ecological processes and the **concept of keystone species**, or;
  iii) developing a **hybrid approach** based on the above concepts but where tools such as numerical models and Bayesian networks (*e.g.* Borsak *et al.*, 2004; Baran *et al*, 2004 and de Waal, 2004) are combined to overcome limitations in the spatial and temporal extent of the available measurements/data and deficiencies in our existing understanding of physico-chemical and ecological processes. Bayesian networks also have the advantage of explicitly handling and clearly articulating uncertainty.

- Due to the complexity and diversity of the ecosystems under consideration and typically limited measurement/monitoring data, there is a requirement to **explicitly make allowance to engage specialists with an adequate understanding of the local physico-chemical and ecological functioning of the system under consideration, particularly in the early stage of the assessment when deciding upon appropriate keystone species and an appropriate ecosystem extent (biogeographic domain) for the assessment.** The outcome of an initial assessment of the role of freshwater in South African marine environments in this study suggests the need for the extensive engagement of such specialists in the early stage of assessments to elucidate **life cycles of appropriate indicator or keystone species**, particularly **those stages of the life-cycle where there is the greatest vulnerability to changes in habitat associated with reduction of freshwater inflows** to the marine environment;

- **Take cognisance and build on the existing management approach in rivers, wetlands estuaries and groundwater environments,** such as the approach of **Resource Directed Measures** used for the management of rivers, wetlands, estuaries and groundwater as it is likely to provide a good starting point for developing a framework to assess potential impacts of freshwater reduction on the marine environment (DWAF, 2004);

- Consider additional, probably **uniquely South African issues (i.e. deficiencies in existing legislation, limited funding, *etc.*)** when developing an appropriate assessment and management framework for managing South African marine environments in terms of their freshwater requirements;

The most important limitation in this regard is likely to **be potential resource limitations** (both human resource capacity and funding). The assessment of the extent and significance of the potential impact of changes in freshwater flow and sediment discharges on ecosystem integrity in coastal and offshore marine environments can be undertaken on a number of levels characterised by increasing complexity, cost and confidence in the outcome, namely assessments of a desktop, rapid, intermediate and comprehensive nature (see Part II: Section 2). Desktop studies may prove to be superficial while comprehensive assessments may be too costly to implement unless a specific and strong motivation exists for their implementation. Thus there is a significant likelihood of only "rapid" or "intermediate" type assessments (in terms of resources available to the assessment) being supported when assessing the potential impacts of changes in freshwater flow to marine environments. Similarly, research funding to better understand the natural functioning of the marine ecosystems and their response to changes in freshwater inflow and sediment discharges, is expected to be limited. Thus there is a need to integrate measurement and modelling activities with existing expertise to undertake "rapid" or "intermediate" type assessments of the extent and significance of potential impacts on ecosystem integrity and functioning due to changes in freshwater flow and nutrient and sediment discharges into marine environments.

4. A Proposed Assessment and Management Framework

An appropriately comprehensive and robust assessment and management framework for the marine ecosystems that takes cognisance of their freshwater requirements, requires an approach (see Figure 1) that includes the following steps:

- **Determination of legislation and policies of relevance:** In developing an appropriate legislative framework, cognisance needs to be taken of the policies and legislation of relevance to the assessment and management of the freshwater requirements of the marine environment, including particular obligations under various treaties and international agreements.

- **Definition of ecosystem extent (biogeographic domains):** The boundaries of ecosystem extent (biogeographic domains) of relevance to the assessment need to be defined based on the extent of the marine ecosystem potentially impacted by change of freshwater inflow (*i.e.* an appropriate definition of the ecological "footprint").

- **Mapping of recognised resource utilization in ecosystem (biogeographical domain)**: The recognised resource utilization in each biogeographical domain needs to be mapped in order that, as a minimum, appropriate keystone/indicator species can be selected for the assessment of the freshwater requirements of the marine environment. In addition, an adequate description of ecosystem and its key components is required to ensure an appropriate ecosystem management approach and the appropriate maintenance of biodiversity.

- **Setting of management and environmental quality objectives:** Based on the identified policy and legislative requirements, recognised resource utilisation and characteristics of the ecosystem under consideration, specific management and environmental quality objectives need to be developed.

- **Scientific Assessment studies** need to be undertaken as follows:

    - *Selection of keystone or indicator species*: Based on the management objectives, the defined biogeographical domains (*i.e.* spatial extent of the ecosystem of relevance) and recognised resource utilization within those domains, keystone and/or indicator species need to be identified that will minimise the complexity of the assessment, allow for the setting of clear and measurable environmental quality objectives and ensure practical and effective management advice.

    - *Determination of life-cycle and habitat requirements*: An analysis of the various life-cycle stages of the identified keystone or indicator species is required to identify the habitat requirements for the various life-cycle stages and consequently the abiotic (and biotic) drivers of relevance.

    - *Identification and assessment of relevant habitat components (drivers)*: The critical abiotic drivers (*e.g.* salinity, nutrients, sediments, *etc.*) influencing the quality of the required habitats during the various life-cycle stages of the keystone species need to be identified. For some species it may be required that biotic drivers need to be selected as well. However, to limit the complexity of the assessment, this should be avoided if at all possible. Where this cannot be avoided, ideally such biotic drivers should be represented by an index based on an appropriate combination of the abiotic drivers of relevance. This also includes an analysis of the temporal and spatial scales required to adequately characterise the drivers and their role in the biotic response of the keystone species chosen.

    - *Spatial and temporal characterisation of relevant drivers (or habitat components)*: The various abiotic (and biotic) drivers need to be integrated and/or aggregated, such that they are relevant to determining the biotic response, *i.e.* they need to be integrated on temporal scales similar to the biological response times and aggregated over spatial scales over which this biological response occurs. Appropriate characterisation of the relevant drivers require appropriate spatial and temporal resolution within the time series characterising the drivers and also that these time series are of sufficient duration to develop robust driver-response relationships. Where the abiotic (and biotic) driver cannot be measured on the temporal and spatial scales required to adequately characterise the driver, an attempt should be made to characterise the driver based on a functional relationship based on a time series that has indeed been measured on the spatial and temporal scales required.

    - *Selection of appropriate assessment methods*: The assessment method or technique (*e.g.* correlation analyses, numerical modelling, Bayesian networks, *etc.*) selected needs

to be consistent with the quantity and quality of the data available and the resources allocated for the assessment.

- *Identification of information requirements*: The data and information requirements (*e.g.* measured or modelled time series) either to directly or indirectly characterise the drivers on the required temporal and spatial scales, need to be determined. Based on these requirements, it may be necessary to undertake specific field measurements or modelling studies to meet these data requirements. It may however be that these data already exist and just need to be collated and analysed.
- *Recommendation on future studies*: Finally, depending on the outcome of the preliminary assessment, recommendations need to be made on additional measurements/modelling studies and/or research required to ensure a robust assessment.
- *Integration and recommending of freshwater flows:* The results of the various keystone species analyses need to be integrated to provide a holistic assessment of the effects of changes in freshwater inflow to marine environments. Recommendations will need to be made on probable allowable changes in freshwater inflow into the marine environment, within the constraint of maintaining or improving the present health status of the marine ecosystem under evaluation and the optimisation of the existing "goods and services" supported by the natural environment under consideration, as reflected in predetermined Management and Environmental Quality Objectives.

- **Recommendation of Freshwater Requirements:** The adequacy of the scientific assessment will be determined by whether or not there is sufficient understanding and/or measurements to translate management and environmental quality objectives into specific freshwater requirements or target values, based on recognised usage of the marine environment as an existing or potential future resource. Typically this is only possible for a specific coastal and offshore region *once existing and potential future resource utilisation in the region of interest has been mapped* and there is *a reasonable understanding of the functioning of the ecosystems of relevance.*

- **Evaluation of socio-economic importance of marine aquatic ecosystems and resource uses**: The outcomes of the scientific assessment of the potential impacts associated with changes in freshwater inflow into marine ecosystems need to be linked to the socio-economic implications of these changes as this is the primary basis upon which water resource allocations are likely to be made. (Note that there should have been some initial consideration of socio-economic issues when selecting "keystone" or indicator species of socio-economic importance for the assessment.). Based on the outcome of this step, there may be modification of the recommended freshwater requirements for the marine ecosystems under consideration. Further, flow scenarios other than the freshwater flows recommended by the scientific assessment may need to be evaluated.

Thus there exists a potential feed-back loop to the previous step in the process, *i.e.* the scientific assessment studies (see Figure 1).

- **Allocated Freshwater Requirements** Ultimately management institutions (DWAF, DEAT, *etc.*) will need to involve stakeholders in deciding upon the Management and Environmental Quality Objectives for a particular marine ecosystem in terms of its utilisation and the extent to which changes (associated with reduction in freshwater inflows) to both existing and future utilization of the "ecosystem services" of these systems, would be acceptable. Only then would it be possible to decide upon and allocate a specific freshwater requirement for the marine ecosystem under consideration.

The proposed assessment and management framework for the determination of the freshwater requirement of the marine environment is schematised in Figure 1 and is described in more detail in the following sections.

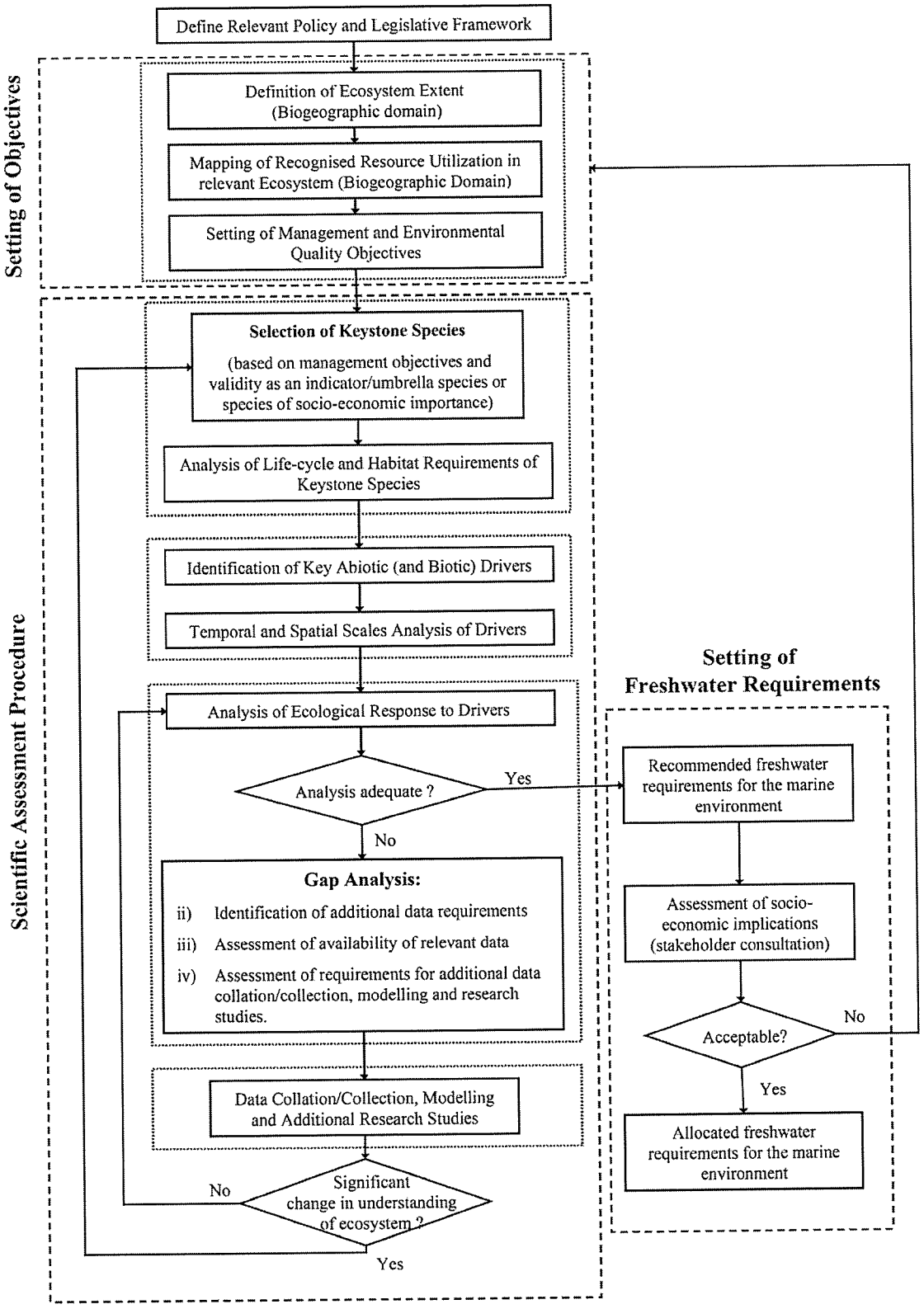


Figure 1: **Proposed Framework for the Assessment of the Freshwater Requirements of the Marine Environment.**

4.1 Legislation and Policies

In setting management objectives for managing the marine environment with respect to freshwater reduction, it is important to identify international and national policies and legislation that list specific obligations or requirements in relation or the protection of ecological services and other resource uses.

4.2 Ecosystem Definition (Biogeographic Domains)

Historically assessment and managements activities have been based on primarily on sectoral interests in terms of resource utilization (*e.g.* fisheries, mariculture, tourism, *etc.*), however a more robust approach is one where the focus is on ensuring the health and functioning of a particular ecosystem and thus the continued flow of ecosystem services supported by that ecosystem (*i.e.* an ecosystem approach). These ecosystem services by definition include the typically multiple sectoral interests in a region.

The boundaries of marine ecosystems are not easily defined because physical conditions and movements of organisms (*i.e.* pelagic life history stage followed by post-settlement movement to other habitats) as well as their prey, fluctuate over large distances in the sea. Ideally the principle should be to define the spatial extent of the ecosystem(s) under consideration (*i.e.* biogeographic domain[9]) in a manner that ensures that the internal trophic flows and/or interactions exceed those occurring across the ecosystem boundaries.

The definition of an appropriate spatial extent for the ecosystem or biogeographical domain for assessment is a significant complication in assessing the potential impacts of changes in freshwater inflows into marine environments, compared to a similar assessments for estuarine environments where the spatial extent of the relevant ecosystem (biogeographic domain) is typically more easily defined, *i.e.* comprises the only the estuary under investigation. To ensure a robust assessment, the boundaries of marine ecosystems (biogeographic domains) need to be defined such that they are sufficiently extensive to encompass the full extent (geographic and ecosystem functioning) of the environment that could be impacted upon (*i.e.* the ecological footprint). Ideally the assumed spatial extent of the ecosystem (biogeographic domain) should encompass the spatial distribution of the keystone or indicator species during all stages of their life cycle. However, such an approach at times may result in an excessively large domain of interest. Should more than one keystone or indicator species be selected for the assessment this may result in biogeographical (ecosystem) domains of potentially widely disparate spatial extents. Furthermore, in increasing the biogeographical (ecosystem) domain extent, it may be that additional keystone or indicator species may need to be considered.

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9 In this report ecosystem extent and biogeographic domain are used interchangeably. Specifically, the use of the terminology "biogeographic domain" refers to the ecosystem extent of relevance based on the ecosystem component included in the particular assessment under consideration.

It may be possible to reduce the extent of the biogeographical (ecosystem) domain by limiting the assessment to only the most sensitive life stages of the keystone species under consideration. Often the biogeographic domain of relevance is less extensive if only a limited part of the life-cycle of the keystone species is considered (*e.g.* the sensitive larval stages of the various species). This approach has the added advantage of significantly reducing the complexity of the assessment.

As suggested above, in each of the identified biogeographic domains, one or more keystone or indicator species needs to be selected as being core to the assessment (see Part I: Section 4.5.1). Where the full life cycle of the keystone species is undertaken within the demarcated ecosystem (biogeographic domain), all life cycle stages and associated habitat requirements and the abiotic (and biotic) drivers determining these habitats are considered. Where only some life stages of the life cycle of the keystone and/or indicator species are completed within the designated ecosystem (biogeographic domain), only those life stages and their habitat requirements are assessed within that designated ecosystem (biogeographic domain). The remaining life stages of the life cycle that are completed beyond the designated ecosystem extent (i.e. within other biogeographic domains) will form part of the assessment within those domains[10].

As noted in above, the selection of keystone and/or indicator species and an associated biogeographic domain of relevance is a potentially iterative process due to the typically unique relationship that exists between a specific keystone or indicator species and its associated domain of influence.

To avoid this potentially iterative process (that proved to be a significant stumbling block of the initial workshop of this project), we propose an approach whereby the marine environment can *a priori* be separate into biogeographic domains, based primarily on:

- the nature of the freshwater flows (*i.e.* surface runoff and coastal and submarine groundwater discharges) into the marine environment;
- the prevailing metocean conditions within the marine environment (*i.e.* physico-chemical classification of the coastal and offshore domain in terms of retention zones, *etc.*); and
- the distribution of marine biota (*i.e.* biogeographic classification of coastal and offshore oceanographic environments).

10 For example, observed short term correlations of King mackerel catches with freshwater flows in KwaZulu-Natal are likely to be false due to the fact that recruitment into the fishery is related good conditions for spawning and larval survival off Mozambique associated freshwater inputs into the marine environment off Mozambique.

The *a priori* selection of the spatial dimensions of the marine ecosystem (or the biogeographical domain)[11] to be assessed, avoids many of the difficulties described above.

The difficulty of making the selections above emphasises the need to **adequately engage domain specialists in the early stage of the assessment, when choosing both appropriate keystone and/or indicator species and an associated ecosystem extent (biogeographic domain) for an assessment** or, in the approach suggested here, the appropriate keystone and/or indicator species and their life cycle stages and associated habitat requirements relevant to the biogeographic region under consideration.

4.2.1 Nature of freshwater inflow

Freshwater inflow to the marine environment can occur through two primary routes, namely:

- Surface runoff entering through rivers/estuaries;
- Submarine groundwater discharges (SGD)[12].

Although submarine groundwater discharges to the marine environment influence similar drivers to the reduction of freshwater inflows from rivers (*i.e.* changes in salinity, temperature, nutrients and cueing effects), groundwater is considered separately in this report due to the fact that groundwater inflows to the marine environment are significantly different in nature and extent to those from rivers. Furthermore, exploitation of groundwater resources resulting in reduced groundwater inflows into the marine environment are likely to have quite different spatial and temporal scales of impact than the reduction of freshwater inflows to the marine environment from rivers and estuaries.

Surface Runoff

Surface freshwater run-off depends primarily on climate and the physical characteristics of the catchments and is relatively well characterised for South African rivers, but less so for estuaries and the South African marine environment.

Submarine Groundwater Discharges

While surface water inflows to the marine environment are reasonably well understood and described, the magnitude of submarine groundwater discharges into the marine environment typically is not. For this reason a short description of the nature and likely consequences of submarine groundwater discharges follows.

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11 Note: An alternative method would be to identify the keystone or indicator species of relevance and demarcate the biogeographical domain of interest based on the full life cycle and habitat requirements of that particular keystone or indicator species

12 Submarine groundwater discharge refers to all water discharged below the high water mark, including that discharged from the beach above sea level at low tide.

Globally, groundwater discharge into the sea is estimated to be about 10% of the volume discharged in surface run-off (Garrels and MacKenzie, 1967 as quoted by Johannes, 1980) while *submarine groundwater discharge* is estimated to amount to only about 1% of surface run-off (Nace, 1970 as quoted by Johannes, 1980). Even though surface run-off dwarfs submarine groundwater discharges on a global basis, a number of observations indicate that submarine groundwater discharges can be of major ecological significance.

Although rivers are the major sources of dissolved and particulate materials for the ocean, submarine groundwater discharges into the marine environment often is a major source of nutrients and other dissolved constituents into the marine environment, particularly nearshore benthic habitats (Johannes, 1980, Capone and Slater, 1990, Valiela *et al.*, 1990). The diffuse nature of groundwater inflows and low flow rates often conceal the fact that the total magnitude of groundwater inflows may be deceptively large due to the fact that typically they occur across a large interface (*e.g.* Cable *et al.*, 1996).

Groundwater discharge to the marine environment globally occurs via at least three pathways:

- seepage flow through nearshore sediments from the surficial (water table) aquifer;
- submarine spring flow; and
- submarine flow from deeper confined aquifers.

These pathways deliver freshwater and re-circulated seawater either as a diffuse (often widespread) seepage at typically low rates over large areas or as point source springs.

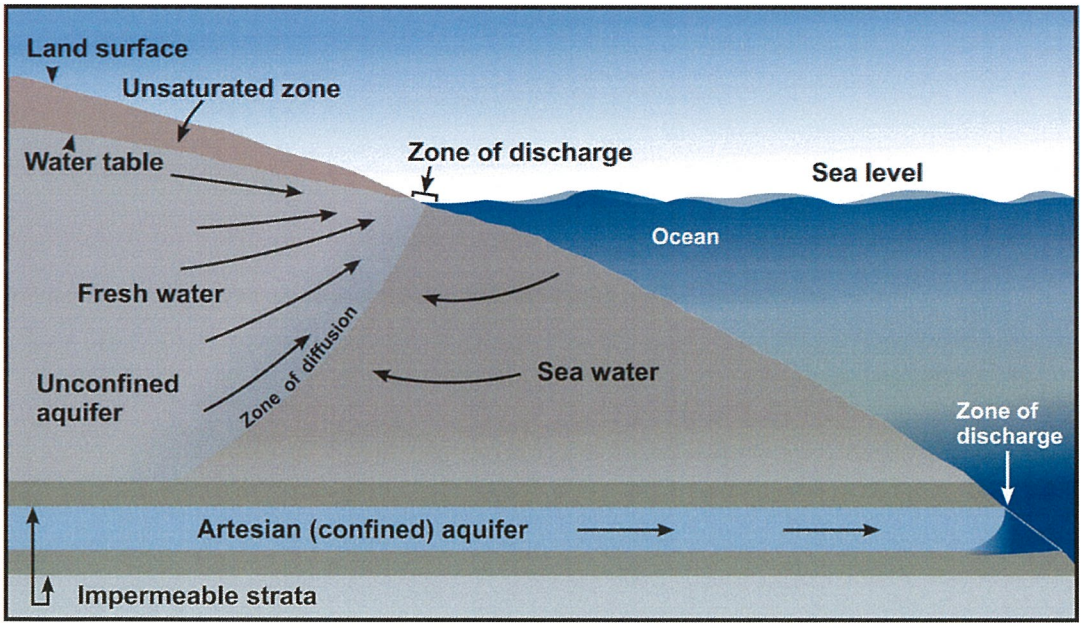


Figure 2: **Idealised representation of submarine groundwater flow (after Johannes, 1980).**

Theoretical models of submarine groundwater discharge from a homogenous unconfined aquifer indicate that the freshwater flows out along the coast through a narrow gap between the freshwater – seawater interface ('zone of diffusion') and the water table outcrop at the beach (see Figure 2). Towards the seaward edge of this zone the seawater will be brackish because of the entrainment of some salt water from the zone of diffusion. The width of the zone of discharge is expected to be proportional to the volume of freshwater flow (Glover, 1959).

The rate of discharge from the zone of diffusion decreases rapidly with distance from the shore (Harr, 1962; Bokuniewiscz, 1980). An underlying salt wedge intrudes beneath the freshwater aquifer along marine coastlines. This wedge impedes the downward mixing of lighter groundwater, thus magnifying the tendency for groundwater from unconfined aquifers to discharge close to shore. Because the beach water table rises and falls in response to the tides but tends to lag behind the tides, the zone of discharge may extend above the water line at low tide (Emery and Foster, 1948).

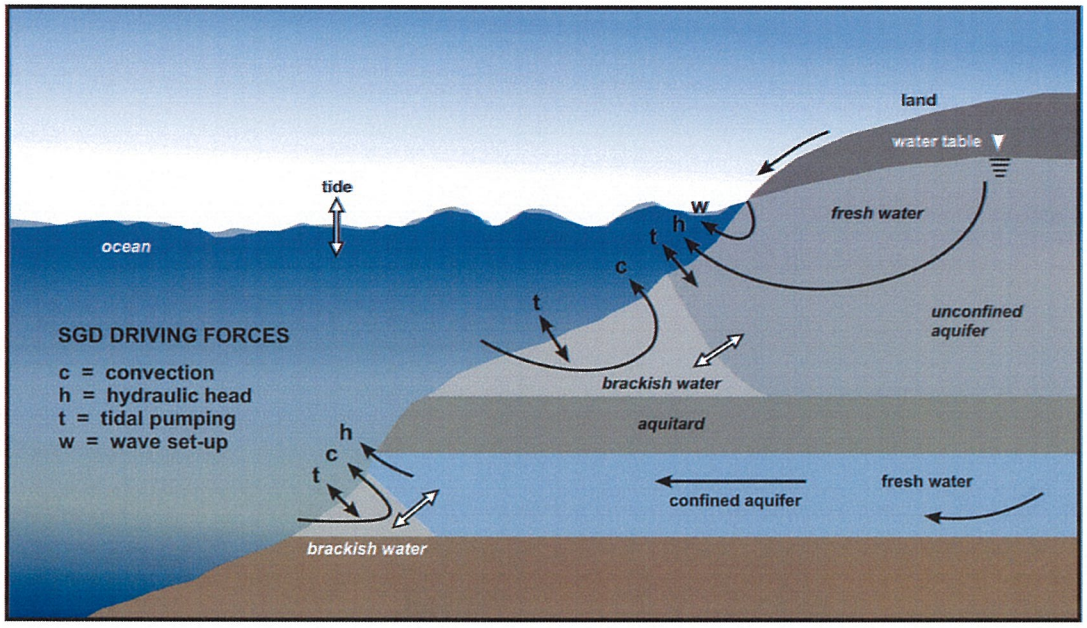


Figure 3: Schematic depiction of processes associated with submarine groundwater discharge and recharge (after UNESCO, 2004 as adapted from M.Taniguchi *et al.*, Hydrological Processes)

Since the groundwater discharge from an unconfined aquifer is restricted largely to the upper portion of the aquifer (see Figure 3), the seaward movement of groundwater at the coast is much greater than the mean rate of coastward movement of water throughout the entire aquifer. Isaacs and Bascom (1949) observed groundwater movement across 10 widely separated beaches along the west coast of the USA that averaged 0.3 $m.h^{-1}$, whereas in the aquifer as a whole the groundwater typically moves towards the sea at a rate of between 1.5 m per year to 1.5 m per day (Todd, 1959). While the above would suggest a strong groundwater inflow close to the coast that

diminishes rapidly on moving seawards, inhomogenous conditions could lead to submarine groundwater discharges from an unconfined aquifer being discharged anywhere within 14 km of the shore (Kohout, 1964). In contrast to unconfined aquifers, confined (artesian) aquifers may outcrop from the ocean floor at any depth or distance from the shore.

4.2.2 Physiography of Coastal Environment and Metocean Conditions

The classification on the coastal and offshore waters into specific ecosystems or biogeographical domains is complicated by the need to consider both the physiography of the coastal environment (*e.g.* the existence of coastal embayments) and the metocean conditions prevailing along a coastal region. The physiographic features and the associated metocean conditions, result in upwelling, retention mechanisms, water column structure, flows, *etc.* all of which determine the relative importance of nutrient and sediment fluxes of terrigenous and oceanic origin in nearshore and shelf environments, as well as the spatial influence of the abiotic drivers associated with freshwater inflows to the marine environment.

4.2.3 Distribution of Marine Biota

There exist fairly distinct biogeographic domain along the South African coastline, that remain similar no matter what ecosystem components are used to make the classification (see Part II: Section 4.3). These biogeographic domains thus provide strong guidance on likely ecosystem boundaries of relevance to this study.

4.3 Recognised Resource Utilization

Recognized resource utilization here refers to both existing and potential future uses of the marine environment as a resource. Resource utilization can be categorized as follows:

- **Ecological services** - this includes the life-cycle and habitat requirements of the key ecosystem components (as defined by keystone species or indicator species as proxies) in the ecosystem or biogeographical domain of interest;
- **Living marine resources** – this includes fisheries (commercial, recreational and subsistence) as well as non-consumptive utilization of marine living resources;
- **Recreation and tourism** – here we restrict ourselves to considering recreation and tourism in terms of primarily coastal development and infrastructure. Non-consumptive utilization of marine resources such as recreational diving, *etc* is best considered under Living Marine Resources (see above bullet). While recreational fishing also could be included here, it is best dealt with under living marine resources;
- **Industrial uses** – this includes mariculture, process water intakes, cooling water intake and discharges, *etc.* However again for reasons of expediency, mariculture is best considered under the heading of Living Marine Resources.

For simplicity we consider only resource utilization that is expected to be significantly affected by changes in freshwater flow into the marine environment, as this is the focus of this study. The review of resource utilization therefore typically is not intended to be exhaustive but rather merely adequate to support the assessment of the potential freshwater dependency of marine ecosystems.

4.3.1 *Ecological services*

Strictly speaking, here one is not considering direct resource utilization in the natural environment, but rather that the life-cycle and habitat requirements of the key ecosystem components constituting that natural environment in the biogeographical domain of interest, are satisfied. These key ecosystem components may be important in maintaining the viability of particular fisheries, general ecosystem function and integrity, biodiversity and/or the protection of rare and endangered species.

Spawning and nursery areas

Mapping of spawning areas is critical in that they will help to define the likely habitats of the early larval stages of most species where survivorship is likely to have its greatest dependency on environmental conditions. It is the habitat requirements for successful spawning and survival of the early life stages that will provide the greatest clues to how changes in freshwater flows to the marine environment and associated changes in habitat/drivers, are likely to impact upon ecosystems. For example, the white steenbras *Lithognathus lithognathus* spawns in July-August off the Eastern Cape (former Transkei) coastline in the vicinity of mud banks deposited by rivers in the region (Bennet, 1993). Changes in freshwater flows may significantly impact upon the spatial extent of such habitats.

Marine Protected areas

Also of relevance in terms of the natural environment are Marine Protected Areas (MPA's) that have more stringent requirements with regards to the maintenance of system function and integrity of marine systems, maintenance of biodiversity and the protection of rare and endangered species in marine systems. It is anticipated that the greater care would need to be taken to ensure that Marine Protected Areas do not suffer any adverse effects due to the reduction in freshwater inflows to the marine environment.

One should however be cautious in assuming that a reduction in freshwater inflows (and associated nutrients and sediments) is necessarily detrimental to the maintenance of system function and integrity of marine systems, maintenance of biodiversity and adequate protection of rare and endangered species in marine systems. For example, in KwaZulu-Natal the MPA's are in areas of least freshwater and sediment inflow, generally because they protect reefs and specifically corals which are sensitive to suspended sediments in the water column. The Kosi MPA is an exception, but inflow waters there have very low suspended sediment.

4.3.2 *Living marine resources*

In this context, the exploitation of living marine resources includes fisheries (commercial, recreational and subsistence) as well as non-consumptive utilization of marine living resources (recreational diving, ecotourism, *etc*).

4.3.3 *Recreation and tourism*

Here we restrict the discussion to recreation and tourism in terms of primarily coastal development and infrastructure, where potential impacts associated with the reduction of freshwater inflows to the coastal environment are long-term erosion of the shoreline that may affect coastal developments as well as have negative impacts on recreational beaches and beach amenities. Although recreational fishing could be included here, it is best dealt with under *Living Marine Resources* (see above). Non-consumptive utilization of marine resources such as recreational diving also are considered under *Living Marine Resources* (see above), however maintaining ecosystems to support and sustain eco-tourism activities may include a number of other requirements (*e.g.* maintenance of biodiversity, protection of rare and endangered species, *etc*).

4.3.4 *Industrial utilization*

Industrial utilization of a water resource typically refers to the abstraction of water for industrial processing. While the reduction in freshwater flows to estuaries may impact upon industrial uses (water abstraction, *etc*) similar impacts in the marine environment are unlikely. In fact, in many cases it is the suspended sediments associated with freshwater inflows that are likely to prove problematic for marine intakes in the marine environment. The only industrial impacts associated with changes in freshwater flows anticipated are those associated with water quality requirements for existing and/or potential future mariculture operations. However mariculture operations also are best considered under either *Ecological Services* or *Exploitation of Living Marine Resources* (see above).

4.4 Management and Environmental Quality Objectives

The management and environmental quality objectives need to be defined for a particular biogeographic region based on legislative requirements, the proposed management approach, resource utilization[13] in the region of interest and the keystone species (or indicator species, umbrella organisms, socio-economically important species) selected as being reliable indicators of the ecosystem attributes of importance (*e.g.* reliable indicators of abundance of commercially

[13] Resource utilization here refers to existing or potential future resource utilization and consequently is likely to include issues such as the maintenance of biodiversity and the protection of endangered species.

important species, ecosystem function/integrity, biodiversity, *etc)*[14]. Appropriate management and environmental quality objectives are required to ensure, for example, the:

- **adequate protection of Marine Living Resources**, especially those subject to important socio-economic activities such as
  - commercial exploitation (*e.g.* prawn trawling industry, deep water crustacean fisheries)
  - recreational line fishing,
  - commercial diving ,
  - subsistence fisheries and harvesting of marine resources (*e.g.* filter feeders), particularly those promoting and ensuring sustainable livelihoods.
- **adequate protection of coastal an offshore environments utilised for socio-economically important activities such as Recreation and Tourism** (*e.g.* preservation of ecosystems in support of ecotourism, the avoidance of as long-term erosion of coastal developments and alteration of recreational beaches)
- **maintenance of ecosystem function and integrity** of marine systems, particularly in Marine Protected Areas[15]
- **maintenance of biodiversity and adequate protection of rare and endangered species** in marine systems. (It should be noted that, in general, biodiversity issues are poorly dealt with in existing assessment and management frameworks due to the perceived inadequacy of available metrics.)

The Management and Environmental Quality Objectives[16] chosen typically are expressed as Environmental Quality Objectives for the Ecology but are expected to include economic and social objectives. Environmental Quality Objectives for the marine environment initially need to be determined by a team of marine specialists, based on the habitat requirements of the various life-cycle stages of the keystone species or indicator species of relevance in the biogeographic domain under consideration. Environmental Quality Objectives could include specifications to ensure adequate protection of Marine Living Resources, especially those subject to important socio-economic activities such as commercial exploitation (*e.g.* prawn trawling industry, deep water crustacean fisheries), recreational line fishing, commercial diving, subsistence fisheries and harvesting of marine resources (*e.g.* filter feeders). For example, an appropriate Environmental Quality Objective for the recreational line fishery of KwaZulu-Natal is the need to ensure the

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14 It should be noted that very often the fisheries species having an economic and social value are the only species for which sufficient life history information and long-term abundance data (in the form of catch) are available to assess the effects of changes in freshwater inflows and are thus by default are used as keystone species or indicator species in assessments and management activities.

15 Special care is likely to be required to ensure that the coastal and offshore marine environment within and in the vicinity of MPA's receive sufficient freshwater where this is required to ensure ecosystem integrity and function and the appropriate maintenance of biodiversity and protection of endangered species.

16 While Environmental Quality Objectives essentially comprise narrative statements on the desired quality level of the environment for the purposes of management these need to be translated into specific Environmental Quality Standard or Specifications related to, for example, freshwater and sediment quantity and quality.

availability of appropriate nursery areas at times of the year when this is critical for estuarine-dependant line fish. Similarly for the prawn fisheries of KwaZulu-Natal it may be important to specify that adequate loads of dissolved nutrients and particulate organic matter reach the relevant marine environments during critical periods of the life cycle stages of the prawns. In Marine Protected Areas it is expected that the Environmental Quality Objectives will be somewhat more stringent and in line with ensuring as near to a "pristine" stock status as possible, the maintenance of biodiversity and the protection of rare and endangered species. Environmental Quality Objectives are likely to also stipulate other less obvious requirements such as preservation of ecosystems in support of ecotourism, the avoidance of long-term erosion of coastal developments and alteration of recreational beaches, *etc.*

4.5 Scientific Assessment Studies

4.5.1 Keystone and/or indicator species

Given the complexity and diversity of ecosystems, the typically limited data available and the limited time and resources typically available to make such assessments, the selection of keystone and/or indicator species is essential in minimising the complexity of the assessment and ensures practical and effective management advice.

It is important to make the distinction between keystone and indicator species. The definition of **keystone species** remains controversial (Davic, 2003). Power *et al.* (1996) suggests a broader definition of a keystone species as "those species whose existence have an effect on an ecosystem that is large, and disproportionately large, relative to its population within that ecosystem" (in contrast to dominant species, which are large populations of species in a given ecosystem)." However a simpler definition might be: "Species populations which play crucial roles in an ecosystem community, and whose removal would have a profound effect on the composition, structure and functioning of that community". Davic (2003) has suggested that a keystone species is a strongly interacting species whose top-down effect on species diversity and competition is large relative to its biomass dominance within a functional group. In this study the definition preferred is that keystone species are "species populations which play crucial roles in an ecosystem community, and whose removal would have a profound effect on the composition, structure and functioning of that community".

Indicator species on the other hand are those species that are reliable indicators of the potential impacts expected, in this case impacts associated with the reduction of freshwater inflows and associated fluxes into marine ecosystems. Criteria that should be considered in the selection and prioritisation of indicator species for any assessment are that the biotic indicator:

- is **particularly sensitive to potential impacts associated with changes in freshwater inflow into the marine environment and water quality, such as changes in nutrient inputs and sediments into the marine and/or availability of nursery environments.**

Typically such a biotic indicator species would be organisms at lower trophic levels with a short life cycle, where the direct effects are more easily and unequivocally observable. In the case of higher trophic levels with longer life cycles, a more sensitive indicator could be a life cycle stage that is particularly vulnerable to the abiotic and/or biotic changes resulting from changes in freshwater inflow, *e.g.* the planktonic larval prawns (*e.g.* Demetriades *et al.*, 2000; Forbes and Dmetriades, 2005) and the larval stages of fish (Connell, *pers comm.*.). However, typically such an approach will give little measure of long-term and/or cumulative change. Ideally the selection of biotic indicators should also present a **balance between indicators that provide "early warning" signals and those that reflect longer-term, more cumulative effects** (*e.g.* longer-lived fish species).

- is considered to be on a "**trajectory of change**" or that the keystone species or biotic indicator is particularly sensitive to abiotic components that are on a 'trajectory of change'
- is considered to be representative of **the important food chains/webs present in a particular system.** This will ensure an appropriately integrative measure that also allows consideration of "cause and effect" links, a key requirement for effective management of the marine environment (*e.g.* phytoplankton production and associated detrital loads that are critical food resources during the vulnerable larval stages of prawns and fish that both constitute important fisheries species).
- is considered to be of **regional or national biodiversity importance.** Guidance in this regard is provided by documents rating the conservation and biodiversity importance of South African estuaries (*e.g.* Turpie *et al.*, 2002, Turpie, 2004) and the South African marine environment (Lombard and Strauss, 2004).
- is an appropriate measure of **health and abundance** of the relevant living marine resource, where exploitation of the resource is socio-economically significant.

It also follows where species have been listed explicitly in the Ecological Specifications (part of the Resource Quality Objectives) of the estuaries component of the Resource Directed Measures assessment, these should be considered for inclusion as a keystone or indicator species in the marine environment assessment in order to link the estuarine domain to that of other marine ecosystems. In this report, for pragmatic reasons (*i.e.* the difficulty of identifying and obtaining consensus on keystone species[17], the availability of data typically that of fisheries, *etc*), it is indicator species of relevance to Environmental Quality Objectives such as the maintenance of biodiversity, ensuring an optimal and sustainable fishery, *etc.*, that are utilised in the assessments.

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[17] In many cases the identification of keystone species may be the subject of endless dispute while it may be more easy to achieve consensus on what constitutes an indicator species (*e.g.* a species most sensitive to changes in freshwater flow into the marine environment whether or not it is key to the functioning of the ecosystem.). A potential added complexity in choosing appropriate keystone species or biotic response indicator species is that potential "indicator groups" may have vastly different or even incompatible needs. For example, along the KwaZulu-Natal coast conservation requirements often concentrate on silt sensitive species while assessments of the freshwater requirements of the marine environment usually focus on silt tolerant (reliant) species, *i.e.* conservation management and water resource management seem to have different "Environmental Quality Objectives". Along the KwaZulu-Natal coastline this issue is somewhat resolved geographically as in the conservation areas of northern KZN there are few large rivers flowing into the sea.

The inclusion of other **abiotic indicators,** such as sediment structure, beach morphology, shoreline erosion, water quality (other than salinity) may be required where:

- there is a high degree of sensitivity of a particular system to changes in such abiotic indicators and the level of interaction of such abiotic indicators with the already selected biotic indicators is high;
- changes in these abiotic indicators have a direct impact (*e.g.* erosion of coastal developments, alteration of recreational beach extents and/or changes in water quality of recreational beaches);
- the particular abiotic indicator is considered to be on a "trajectory of change" (*e.g.* coastal erosion).

4.5.2 Life-cycle and habitat requirements

Two broad approaches to assessing the potential impacts of the reduction in freshwater flows into estuarine, marine environments are described in Section 4.5.6 below. Both require an adequate knowledge of the life cycle and habitat requirements of the keystone species selected.

Proposed mechanisms determining the role of freshwater flow (or the lack thereof) on marine ecosystems typically can be summarised in terms of effects on[18]:

- catchability (typically short-term);
- recruitment (*i.e.*, survival particularly during the early stages of life, translating into the "strength" or size of a cohort);
- productivity (*i.e.* increased growth rates resulting in higher biomass/stocks).

There is considerable complexity in the life cycles and habitat requirements of most keystone and/or indicator species, the complexity typically increasing with the longevity of the species under consideration. It is common for the various life-cycle stages of a particular species to have significantly different habitat requirements (salinity and nutrients, trophic regimes, requirement for nursery areas, *etc*). Only once the various life-cycle and habitat requirements have been adequately characterised is it possible to determine the range of drivers (both abiotic and biotic) that will have to be characterised by measurement or modelling in order that an adequate assessment can be made of the potential impacts of changes in freshwater inflow into the marine environment on the keystone species under consideration. Typically, these habitat requirements and their dependence on freshwater inflows will need to be characterised in terms of the volume, timing, seasonality, inflow rate, *etc* of the freshwater flows. The challenge thus is to accurately

[18] Typically all of these factors are integrated when assessments are made utilising CPUE, however such assessments do not, and often cannot, easily discern the detailed mechanisms underlying the relationship between CPUE and the various drivers. This typically requires additional measurements and analysis of one or more of the above three factors (*i.e.* catchability, recruitment and productivity) and the drivers of relevance.

determine the freshwater flow needs of the marine environment and to include these requirements in water allocation processes where appropriate.

Robins *et al.* (2005) have provided an overview of the effect of freshwater flows on the estuarine fisheries of tropical Australia. Most of the concepts used are equally valid for assessing the effects of changing freshwater flows on coastal and offshore marine ecosystems. The assessment criteria of Robins *et al.* (2005) are based on the categories of freshwater flow effects identified by Drinkwater and Frank (1994), namely spawning success, advection of eggs and larvae, migration, competition and distribution, general productivity and food supply, and water quality . Examples of the life-cycles requirements identified by Robins *et al.* (2005) are:

- **Penaeid prawns**: Penaeid prawns are short-lived (*i.e.*, one to two years), opportunistic omnivores that are dependent on estuarine habitats for part of their life cycle, but have different preferences of habitat type, degree of emigration and tolerance of low salinity. Correlations between freshwater flow (or rainfall) and catch, mostly have been reported for those species with the greatest tolerance or exploitation of brackish-water habitats and, in general, significant positive relationships are reported between annual catch and total freshwater flow (or rainfall) in the same or previous year (*e.g.* Glaister 1978; Vance *et al.* 1985 and Gammelsrod 1992). Significant within-year correlations between catch and monthly or seasonal freshwater flow (or rainfall) have also been reported (*e.g.* Glaister 1978; da Silva 1985; Gammelsrod 1992; Vance *et al.* 1985, 1998). As noted previously, the relationships between prawn catch and freshwater flow (or rainfall) are potentially confounded by other factors such as fishing effort and spawning stock size, their degree of influence depending on the level of exploitation of the population by the fishery. (Most of the correlative relationships for prawns do not account for these factors.) Suggested causal mechanisms for the observed relationships between the catch of penaeid prawns and increased freshwater flow (or rainfall) noted by Robins *et al.* (2005) include:
    - enhanced emigration of prawns to areas accessible to the fishery, leading to increased catchability,
    - enhanced growth and survival of various life stages leading to increased abundance or biomass due to enhanced recruitment from "enlarged" nursery areas and enhanced food availability associated with increased primary and secondary productivity.
- **Finfish species:** Relationships between commercial catch and freshwater flow have been published for a number of tropical (or sub-tropical) finfish species (*e.g.* in sub-tropical Australia, significant positive correlations between catch and freshwater flow were found for mullet (*Mugil spp.*) and flathead (*Platycephalus spp.*) (Loneragan and Bunn, 1999).

  Suggested causal mechanisms for the observed relationships between finfish catch and freshwater flow include:

- changes to catchability (*e.g.* Loneragan and Bunn, 1999; Lamberth as reported in Louw, 2003; Lamberth and Drapeau, 2007),
- changes in spawning intensity and cohort or year-class strength during the first year of life (Quiñones and Montes 2001; Demetriades *et al.*, 2005) and,
- changes to food availability via productivity changes resulting from flow-borne nutrients (Aleem, 1972; Salen-Picard *et al.*, 2002).

Effects on catchability are likely where there is a correlation between catch and freshwater flow in the same year (*i.e.* an immediate response), while effects on year-class strength are suggested where correlations are between catch and freshwater flow lagged by the period that it takes individuals of the species to "recruit" to the fishery (Lamberth 2003; Lamberth and Drapeau, 2007; Robins *et al.*, 2005). Potential mechanisms resulting in changes in recruitment include:

- advection (negative effect) or retention (positive effect) of eggs and larvae in nursery areas (*e.g.* Hutchings *et al*, 2002),
- increased predation (negative effect) of a year class (young-of-the-year),
- changes in the spatial extent and availability of suitable reproductive and nursery habitats; and
- improved food availability for larvae and juveniles (Quiñones and Montes 2001; Salen-Picard *et al.* 2002).

In terms of the habitat requirements of keystone or indicator species, two generic life cycles are of interest, namely those of **shorter-lived species** (*e.g.* prawns) and **species of greater longevity** (*e.g.* line-fish) that are influenced by changes in freshwater inflows to the marine environment. Examples of the life cycles of both shorter lived species and species of greater longevity are given in Appendix B. The schematised pathways of factors influencing catchability, recruitment and productivity provide a good example of the level of detail required (and some of the complexities involved) to make a robust regional assessment of the influence of the reduction of freshwater inflows to the marine environment.

Similar life-cycle descriptions and associated habitat requirements for the KwaZulu-Natal coastline (prawns and selected line fish) are discussed in greater detail in Part II: Section 7 that contains the regional assessments of the influence of freshwater flows on marine environments of South Africa.

Newman and Weerts (2007) have recently undertaken a study to select indicator species for determining catchment to coast and alongshore connectivity in the marine ecosystems of KwaZulu-Natal.

4.5.3 Relevant habitat components (drivers)

Based on the life cycle and habitat requirements of the selected keystone or indicator specie(s) it should be possible to select the critical abiotic drivers (*e.g.* salinity, nutrients and sediments, *etc*)

influencing the quality of the required habitats during the various life-cycle stages of the keystone species. It may be that for some species biotic drivers may need to be considered as well, however to limit complexity and ensure the development of a robust predictive capability, this should be avoided wherever possible.

As most effects on the keystone or indicator species under consideration are one or more steps removed from the direct changes in physical parameters (*e.g.*, water velocity, salinity, water temperature, turbidity) that result from freshwater inflows, a clear distinction is made here between:

- abiotic and biotic drivers to which there is a direct ecological response, and
- other indirect measures such a freshwater flows to the marine environment that characterise drivers such as nutrient (dissolved and particulate) inputs and sediment discharges to the marine environment, but rarely result in a direct ecological response themselves. (For example, freshwater flow itself can only be considered a driver when there is a direct ecological response to, or consequence of, the physical displacement of biota or a flow-related phenomenon such as the erosion of sediments leading to a reduction in the extent of a particular habitat.)

The temporal and spatial scales of relevance in characterising the drivers are:

- **the temporal and spatial scales at which the biota responds to the various drivers:** The various abiotic (and biotic) drivers need to be integrated and/or aggregated, such that they are relevant to determining the biotic response, *i.e.* they need to be integrated on temporal scales similar to the biological response times and aggregated over spatial scales over which this biological response occurs. For example, elevated nutrient levels need to persist in the marine environment for days to weeks for there to be a significant response in phytoplankton and benthic micro/macro algae.
- **the temporal and spatial scales that need to be resolved in order to adequately characterise the drivers:** The temporal scale at which a driver needs to be measured/simulated depends on the variability in the driver, both at sea and in river inflow. Drivers associated with the water column (*e.g.* dissolved nutrients) typically have a characteristic variability of hours to days to weeks. Drivers associated with the sediments (*e.g.* particle size distribution defining a habitat) typically show variability of weeks to seasons to possibly decades, depending on the deposition/re-suspension characteristics of the study area.
- **the duration and spatial extent of the data record required to adequately characterise the drivers and to quantify the relationships between driver(s) and the biotic response:** For example, to be able to predict the relationship between the "state of the mouth" and river flow, a data record of between 5-10 years duration comprising daily recordings of both parameters will be required. For lower trophic levels, *e.g.* primary producers and zooplankton, a relatively high resolution data record of 1 to 2 year

duration may be sufficient. However, for higher trophic levels data sets extending over 5 to 10 years duration or more, are required.

From the initial assessment workshop it also became clear that adequate characterisation of many of the drivers requires that **synoptic or event scale** processes are resolved in the hydrodynamic and water quality models, a finding consistent with that from the Catchment2Coast research project (Monteiro and Matthews, 2003). This in turn requires **that freshwater and sediment inputs to the marine environment be quantified on an event scale,** i.e. that the input of freshwater, nutrients and sediments to the marine environment ideally needs to be characterised and assessed using daily data. Such data is rarely available so attempts will need to be made to use lower resolution data in the assessments.

Surface Runoff

The primary drivers related to changes in freshwater surface inflows into the marine environment surrounding South Africa are listed below.

- **Availability of estuaries as nursery areas:** Possibly the most important of the ecosystem services provided by an estuary to the marine environment is that of a nursery area for estuarine-dependent marine biota. Availability of such a nursery function for marine biota with an estuarine dependency, firstly requires that the estuary is accessible at the times needed (*i.e.* the mouth needs to be open) and, secondly, that the health of the estuary is such that the estuary remains an appropriate habitat for estuarine dependent marine-biota, *i.e.* the relevant physico-chemical distributions and required habitat-forming flora and fauna are present (*e.g.* mangrove habitats have been recognised as particularly important during juvenile development of shallow water penaeids (Weerts *et al.*, 2003)). It may be that the mouth of the estuary is open but the estuarine health is so degraded that the estuary is no longer able to function optimally as a nursery area. Conversely, the estuary may be sufficiently healthy to provide the necessary nursery function but due to mouth closure may not be accessible to marine biota seeking a nursery area. For this reason both "*estuarine mouth condition*" and "*estuarine habitat suitability*" need to be considered as separate but complementary drivers.

  The nursery function or availability of a nursery habitat is critical to a number of invertebrate and fish species. There are a number of estuarine dependant categories of fish (Whitfield, 1998; Viljoen and Cyrus, 2002), ranging from species completely dependant on estuaries through species with varying dependence on estuaries and catadromous species (*i.e.* species that use estuaries as transit routes between marine and freshwater systems) to marine species that are not dependent on estuaries. Similarly there is a range of estuarine dependencies for invertebrates. For example, the postlarval stage of shallow water penaeid prawns generally enters estuaries (recruitment) during July to September and remains there for approximately on average 8 months (Demetriades and

Forbes, 2003)[19]. The juvenile prawns start leaving estuaries (emigration) during February to March. Estuaries also may form movement corridors for river invertebrates that breed in the marine environment (*e.g.* river crab *Varuna litterata* – Whitfield, 1998).

"*Estuarine habitat suitability*" should generally be ensured if the estuary is appropriately managed under the DWAF Resource Directed Measures (RDM) process. It may be that over time the estuary has deteriorated as a nursery habitat for marine biota with an estuarine dependency, however this is likely to be noticed in the monitoring protocols for the RDM process and appropriately managed. In terms of protecting the marine environment, it is important that the nursery function of an estuary for marine biota is monitored and maintained.

The "*estuarine mouth condition*" not only allows for recruitment into the estuaries but also, under high flow conditions, allows for the direct export of fish or other biota that were previously trapped in predominantly closed estuaries. The reduction in river inflow could cause an increase the frequency and duration of closed mouth conditions in estuaries along the South African coast and associated changes in estuarine habitats (Morant & Quinn 1999, Whitfield 1998). The management of estuarine mouth conditions to maintain the nursery function of an estuary for estuarine dependent marine biota is thus required, particularly where the reduction in freshwater inflows to the estuary could lead to closed mouth conditions at times when such a nursery function is required. Given that only one or a few of the estuaries along a particular stretch of coastline may be able to provide a suitable estuarine nursery habitat for a particular species, that species at critical periods of its life cycle may be highly sensitive to closed mouth conditions occurring for even one of the estuaries potentially providing such a nursery function. An example is the prawn nursery areas in Natal where only a limited number of nursery areas exist for prawn stocks in the region.[20] It has recently been shown, however, that some estuarine dependant nearshore fish species are able to enter closed estuaries via berm overtopping (Perisinotto *et al.*, 2003; Bell *et al.*, 2001; Cowley *et al.*, 2001).

- **Cueing effects:** Freshwater flows may provide cues for the migration of estuarine-dependant juvenile and adult fish into and out of the estuarine environment. (*e.g.* Binet *et al.*, 1995; Whitfield, 1998; Strydom and Whitfield, 2000; Louw, 2003). Similar cues may exist for invertebrates (*e.g.* prawns, *Varuna litterata*), however there is evidence indicating that prawns do not necessarily require such freshwater-related cues (A. Forbes and Demetriades, 2005, Forbes, *pers comm.*)[21]. The strength of these cues will ultimately dictate

19 Tagging studies indicate that the time spent in the estuary could range from as little as 4 months to over one year, depending on the time of recruitment. (Forbes, *pers comm.*)

20 Along the KZN coast only three systems provide the majority of the suitable nursery habitat for penaeid prawns viz St Lucia, Richards Bay and the Mhlatuze estuary. Penaeids have been recorded in many other estuaries but are not found in high numbers and therefore these are not considered to constitute significant nursery areas (Demetriades, 2003).

21 For example, prawns were still present in the St Lucia narrows during periods when the lake was hyper-saline, i.e. > 35 psu. Similarly, the Shark Bay area in Western Australia supports a major prawn fishery despite the fact that the absence of rivers means that salinity increases into the bay.

how many individuals of these species will recruit into the marine fisheries. Similarly freshwater inputs to the marine environment may provide spawning cues. The exact nature and physiological basis of this cueing effect is not yet understood, although evidence exists that it may be olfactory in nature. In this regard, a knowledge and understanding of the *spatial extent and persistence* of the cues are important.

- **Availability of physical habitat as defined by the distribution of marine sediments:** Here we consider mainly inorganic sediment loads into the marine environment and their deposition in coastal and offshore environments to provide an appropriate physical habitat (*i.e.* a substrate for colonisation by primarily smaller benthic organisms, invertebrates and benthic fish). Organic sediments are also considered where, through their deposition on the seabed, they help to create a physical habitat suitable for various marine organisms. It is not only the *quantity of sediment* being discharged into the environment but also the *nature or quality of the sediments* (*i.e.* grain size distribution and organic content) that is of importance. The quantity of sediments discharged into the marine environment determines the potential spatial extent and depth of sediments providing a suitable habitat for marine biota, *i.e.* changes in the extent of suitable habitat. The grain size distribution and organic content, in turn, determines both the initial distribution and ultimate fate of the sediments in the marine environment and also whether the deposited sediments actually constitute a suitable habitat for the various life stages of marine biota under consideration. Similarly, the strength of flows leaving the mouth of estuaries determines the initial extent of the plume containing particularly the fine sediments and consequently, the initial distribution of muds in the adjacent marine environment.

  The primary driver thus is the **spatial extent of a physical habitat** available to the various life cycle stages of species that depend on marine sediments as a habitat. For example, on the KwaZulu-Natal coast the sub-adult and adult stages of shallow water penaeid prawns are expected to have physical habitat requirement based on sediment inputs into the marine environment. Changes in the aerial extent and composition of sediments are likely to influence the relative abundance and community structure of shallow water penaeid prawns (Demetriades *et al.*, 2000). Similarly, the existence of certain substrates are associated with the spawning behaviour of some fish species, *e.g.* off the southeast Cape coast white steenbras *Lithognanthus lithognanthus* is known to spawn in July - August in the vicinity of mud banks deposited by rivers in this region (Bennet, 1993). A possible reason for this is the high concentration of microphytobenthic algae that are much more productive on mud banks than on coarse sand.

  The persistence and spatial extent of the various marine sediments at various cross-shore locations largely determines whether the deposited sediments actually constitute a physical environment of significance and therefore needs to be measured or simulated using sediment transport models.

- **Fronts and other retention mechanisms:** Freshwater inflows to the marine environment will result in the formation of thermohaline fronts. Smaller freshwater

inflows are likely to result in reduced salinities (and changes in temperature) that are confined mainly to the surf-zone where the water column is likely to be well-mixed. In general, freshwater inflows that are retained within the surf-zone are expected to result in fairly persistent changes in the physico-chemical properties of the nearshore waters due to the limited mixing that occurs between the surf-zone waters and the deeper waters beyond the surf-zone.

Significant freshwater inflows to the marine environment will result in large freshwater plumes that extend beyond the surf-zone. Associated with these more extensive freshwater plumes is strong vertical stratification of the water column (mainly beyond the surf-zone) and strong horizontal gradients in salinity and possibly temperature between the freshwater plume and the surrounding waters. Due to prevailing metocean conditions, the changes associated with freshwater plume extending further offshore will be significantly less persistent than those occurring in the surf-zone.

The vertical stratification of the water column is important as it suppresses vertical mixing and in so doing helps ensure that phytoplankton remain in favourable light conditions (and potentially higher nutrient conditions associated with river inflows) that typically results in increased primary production. Horizontal and vertical fronts also are associated with accumulations of phytoplankton, zooplankton and other marine biota and thus provide a concentrated source of food attracting fish, mammals and birds.

- **Nutrient availability in the marine environment**: Nutrients entering the marine environment can be separated into:
    - **dissolved nutrients**, primarily dissolved inorganic nutrients comprising nitrates, nitrites, phosphates, silicates and ammonia, as well as dissolved organic carbon and nitrogen, and
    - **particulate organic carbon and nitrogen** entering the marine environment via direct live organic material and detrital input from river inflows. (Indirect organic carbon fluxes due to phytoplankton production in the marine environment are not considered to be a direct driver as they are a consequence of a combinations of other direct drivers associated with freshwater inflows to the marine environment such as the input of dissolved nutrients, water column stratification and appropriate light conditions. However organic carbon fluxes from estuaries where the nutrient uptake and primary production occurs predominantly within the estuaries, is considered a direct driver.)

Nutrient supply to the marine environment stimulates the production of phytoplankton and zooplankton and ultimately the larval, juvenile and adult stages of invertebrates and fish that depend on them as a food source. Live organic material and detritus may be broken down into useful nutrients, serve as a substrate for micro-flora and fauna or be consumed directly by detritivorous fish and invertebrates.

While there has been a reduction in freshwater flows to the marine environment over time, it is not clear that there is has been a concomitant reduction in nutrient loads to marine environments. Land-use practices may have raised the concentrations of nutrients in estuaries sufficiently to result in largely unchanged or even an overall increase in nutrient loads (*i.e.* freshwater flow volumes multiplied by nutrient concentrations) to marine ecosystems. Certainly in many estuaries, particularly in developed areas, increased nutrient loads (due to fertilisers and other sources such as processed sewage) are a reality. In some estuaries, increased flows due to effluents may have increased both freshwater flow rates *and* nutrient concentration, resulting in significantly greater nutrient loads into the nearshore environments surrounding the mouths of these estuaries, *e.g.* Mdhloti (Perrissinotto *et al.*, 2003) and Kuilsrivier estuaries (van Ballegooyen and Botes, 2000). However while this may result in some benefits to the coastal zone (*e.g.* the export of organics and nutrients) it also disrupts the nursery function of the estuaries by increasing drastically the frequency of mouth breaching.

It is not clear how and to what extent potentially increased nutrient concentrations in estuarine waters, together with change (typically a reduction) in freshwater flows to marine ecosystems, have changed the nutrient loads entering coastal and offshore ecosystems. While higher nutrient concentrations in the water leaving estuaries may in some cases compensate for reduced freshwater flows, there are likely to be changes in both the spatial and temporal distribution of nutrients in marine ecosystems associated with changes in freshwater inflow that may significantly affect the nature of the biotic response in these environments. For example, the distribution of nutrients in freshwater plumes in marine environments are expected to be more extensive for high flow or flood scenarios, while significant changes in the temporal variability of the nutrients loads entering marine environments may occur under changed freshwater flow scenarios.

As noted above, for the purposes of assessment the nutrient inputs into the marine environment have been categorised as either *dissolved nutrients* and *particulate organic matter.*

- **Physico-chemical variables**. Important physico-chemical variables to consider include:
    - *Temperature.* Freshwater inflows to the marine environment may result in significant changes in seawater temperatures both in the nearshore zone and further offshore. For example, off KwaZulu-Natal the difference in seawater temperatures and the temperature of the freshwater inflows to the marine environment is limited. However on the West Coast, the temperature differences between estuarine waters and coastal/offshore waters may be significant. In summer the estuarine waters on the West Coast are significantly warmer that the cold upwelled marine waters[22], while in winter the estuarine waters are likely to be colder than the relatively warm coastal waters observed due to a reduced

[22] This has implications in terms of the aggregation in the nearshore of certain fish species (see the detailed assessments in Part II: Section 7).

occurrence of upwelling during the winter months. Temperature effects include increased metabolism (Q_{10} effect) due to increasing temperatures, *etc.* Furthermore, changes in water temperature due to reduced freshwater inflows may result in deleterious impacts where the resultant water temperatures are outside the range preferred by specific marine biota.

- *Salinity.* As noted above, freshwater inflows to the marine environment will result in decreased salinities in the nearshore zone near the estuary mouths and further offshore, should the freshwater inflows into the marine environment be significant. The extent of the zone of reduced salinity depends both on the magnitude of the freshwater inflows and the metocean conditions prevailing in the marine environment. Low salinity conditions are likely to persist for longer in the surf-zone than in environments further offshore. In terms of freshwater reduction, the impacts related to changes in salinity are associated with habitat reduction where there is a potential reduced tolerance to high salinities or a preference for lower salinity conditions during specific life stages of the keystone or indicator species under consideration.

- *Turbidity.* The grain size distribution and organic content of sediments not only determines the quality of the seabed habitat but also the extent and persistence of water column turbidity in the marine environment. A high percentage of fines in the discharged sediments are expected to result in fairly persistent water column turbidity while a high organic content in the sediments may facilitate flocculation processes that typically increase the rate of sedimentation of fines from the water column. In addition, the extent and rate of accumulation of fines in the marine environment will determine the quantity of fine sediments available for re-suspension and consequently the water column turbidity generated during storm conditions both due to the re-suspension of fine sediments and potential additional inflows of fines to the marine environment from rivers and estuaries.

  Water column turbidity not only reduces the *light availability* for phytoplankton production but also modifies the behaviour of fish and their prey. Increases in water column turbidity tends to increase the catchability of many species (such as slinger, javelin grunter and rock-cods), especially the larger individuals that move into a turbid environment in search of concentrated prey. An elevation in water column turbidity also may have a deleterious effect on biota such as clogging of gills and feedings baskets of filter feeders, *etc.*

  In summary, when considering sediments inputs into the marine environment as a driver of ecological response, the relevant measures are the ***spatial extent of* suitable habitats** (determined by quantity of sediment, grain size distribution, organic content and persistence of sediments in a particular environment) and **water column turbidity** (determined largely by grain size distribution and organic content, as well as the rate and extent of accumulation of fines in the marine environment available for re-suspension).

Reduction in freshwater flows and the building of dams are expected to reduce the sediment discharges into the marine environment. In the case of dams it is likely that there will be a winnowing effect on sediments in that coarser particles tend to settle out in dams (even during flood conditions), while the finer material remains in suspension for longer and is more likely to be transported into estuaries and into the marine environment.

While a reduction in sediments inputs to the marine environment is expected due to diminished freshwater inflows and the building of dams, it is not clear whether changes in land-use have increased the sediments loads in some rivers and estuaries to the extent that there is no significant reduction of sediments to the marine environment. Perhaps in some cases the sediment loads even may have increased (*e.g.* Mbashe and Mgazana estuaries). The assumption that reductions in freshwater flows, particularly floods and freshets, have significantly changed the quantity of sediments discharged into the marine environments needs to be tested[23].. Certainly, changes in freshwater flows are expected to change the nature and timing of the sediment discharges to the marine environment and consequently potentially also the spatial extent and persistence of various sediment-based habitats[24].

- **Biotic drivers:** In principle the drivers considered in the driver-response approach adopted in the initial workshop should be limited to the abiotic drivers that directly drive an ecological response. The ecological response of relevance in such a driver-response model is that response occurring at the lowest trophic levels and at the "first interface" between the abiotic drivers and the ecological response. For example, it may be that the increased phytoplankton production due to the input of dissolved nutrients into the coastal and offshore environment is of relevance rather than the secondary ecological

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23 There is a strong perception that siltation and sedimentation have had the most detrimental effect on (certainly KwaZulu-Natal) estuaries (Begg 1978, 1984). Reference is often made to the "sanding up" at estuary mouths as well as "silting up" in middle and upper reaches of estuaries. Both could be attributable to reduced freshwater flows. Certainly sedimentation of estuary mouths probably results from wave driven sediment transports and flood tide deltas building up (reduced river flow) rather than increased river loads. This in turn could result in siltation further up the system (reduced tidal prisms *etc*). There is an obvious connection between river flow and purging of estuaries of silt accumulations, however bad catchment management and poor land use practises resulting in increased erosion and greater silt (and sediment) loads in South African estuaries (KZN and E. Cape, e.g. Schumann, 2003) is widely accepted as fact and also that these sediment loads are being delivered into our marine environments. This has resulted in the observation that "SA's greatest export is her topsoil".

24 It is expected that the reduction in freshwater flows, particularly floods and freshets will reduce mainly coarse sediment inputs to the marine environments due to changes in the flushing of sediments from the lower or mouth region of estuaries. This reduction in the flushing of coarse sediments is expected to result in shorter to medium-term changes in adjacent shoreline erosion and accretion. However it should be noted that if dams are not large enough to significantly affect major floods (say > 1 in 30 years return period) then the sediment accumulated in the interim in estuaries will still be flushed out and the long-term shoreline equilibrium not affected significantly. The reduction of fine sediment inputs to the marine environment associated with the reduction of freshwater flows (*i.e.* floods and freshets) and the building of dams is expected to be more limited. The impacts here may be more related to the nature of the distribution of these fine sediments, *i.e.* whether the sediments are initially deposited in the nearshore zone, re-suspended and ultimately transported into deeper waters or whether the fines are transported in extensive turbid plums to be deposited further out over the shelf or possibly even advected into deeper water beyond the shelf before deposition can take place.

response of, for example, fish to an increased food source. However, at times, it is not possible to limit assessments to the consideration of ecological responses to abiotic drivers alone and biotic drivers will need to be considered. An example of this is the ecological response to changes in the availability of an appropriate nursery habitat, that in turn is a combination of mouth condition, favourable physical factors and the presence of suitable habitat-forming species such as *Zostera* beds, mangroves, *etc.*

Where considered, such biotic drivers either should be directly measured or represented by an index based on an appropriate combination of abiotic drivers. Alternatively, the abiotic drivers could be utilised as input to appropriate biotic response models (*e.g.* individual-based models) that in turn provide appropriate measures/estimates of the biotic driver(s) of relevance.

The approach taken in the initial workshop of this study was to consider primarily the abiotic drivers (except for the availability of nursery habitats and possibly cueing effects) and to merely note the trophic pathways in the marine environment. The ecological response components considered were phytoplankton, benthic algae, (holo)zoplankton, benthic invertebrates (including larval stages *i.e.* mero-zooplankton), fish, birds, mammals, turtles. Also considered were the physical changes occurring in nearshore environments such as shoreline erosion, *etc.*

Submarine Groundwater Discharges

As noted in Section 4.2.1 above, although **submarine groundwater discharges** to the marine environment influence similar drivers to the reduction of freshwater inflows from rivers (*i.e.* changes in salinity, temperature, nutrients and cueing effects). However, groundwater is considered separately in this report due to the fact that:

- groundwater inflows to the marine environment are significantly different in nature and extent to those from rivers, and;
- the exploitation of groundwater resources resulting in reduced groundwater inflows into the marine environment are likely to have quite different spatial and temporal scales of impact than the reduction of freshwater inflows to the marine environment from rivers and estuaries.

The potential role played by such submarine groundwater discharges (*i.e.* all water discharged below the high water mark, including that discharged from the beach above sea level at low tide) may be summarised as follows:

- **Nutrient fluxes**: Submarine groundwater discharges may play a significant role in maintaining nearshore ecosystems mainly through the *nutrients* associated with groundwater, particularly where one or more of these nutrients may be limiting in the marine environment (UNESCO, 2004). Although submarine groundwater discharge volumes to the marine environment may be an order of magnitude lower than surface

water discharges to the marine environment, the nutrient concentrations in the groundwater, in turn, may be an order of magnitude higher than those in the surface water discharges. Under these circumstances the ratio of ground water nutrients to river nutrients delivered annually to coastal waters bordering an aquifer may be high, *i.e.* significantly greater than unity. Such an observation is made for the coastal region north of Perth, Australia (Johannes, 1980). Examples of the potential role of nutrient inputs associated with submarine groundwater discharges in nearshore ecosystems are:

- the potential association of surf-zone diatom accumulations with known submarine groundwater discharges or conditions expected to lead to significant submarine groundwater discharge, *e.g.* False Bay, Algoa Bay (Campbell and Bate, 1998)
- the more vigorous growth of rooted aquatics observed in the presence of submarine groundwater discharges. However, the vigorous growth may as much be a consequence of reduced osmotic stress as due to elevated nutrient availability arising from submarine groundwater discharges (Johannes, 1980), but nevertheless still a consequence of the presence of submarine groundwater discharge.
- reported relationships between low interstitial salinities (related to submarine groundwater discharges) and the composition of interstitial micro- and meiofauna (Bruce, 1925, Smith, 1955 and Moore, 1979), of overlying algal mats (Sanders, 1979), the presence of burrowing crab (George, 1962), the relationship between groundwater seepage and the composition of seagrass beds and associated fauna (Kohout and Kolipinski, 1967).

- **"Insurance" or refuge role**: As with groundwater inflows to estuaries, submarine groundwater discharges may be important in maintaining freshwater (and nutrient inflows) during periods where surface freshwater inflows into the marine environment are limited due to seasonal or interannual variations and thus may play an "insurance or refuge role" in nearshore environments. The maintenance of submarine groundwater discharges into the marine environment may even play somewhat of a mitigating role should the there be significant reduction of long term freshwater inflows to the marine environment via rivers and estuaries.

- **Cueing effects:** Groundwater flows may also play a role in *cueing effects*. Koch *et al.* (1969) reported that green sea turtles *Chelonia mydas* may use groundwater seepage as a marker for location and recognition of island breeding grounds. Harden Jones (1980) has postulated that plaice *Pleuronectes platessa* may also use ground water seepage as a landmark for identifying spawning grounds. It is possible that groundwater could play a similar role in terms of cueing effects in the nearshore waters of South Africa.

- **Maintenance of nursery function of estuaries:** Groundwater flows into estuarine environments may play an indirect but important role by helping to maintain access to

estuaries (by influencing mouth conditions) and by helping maintain estuarine habitats that are suitable for estuarine dependent marine-biota.

4.5.4 *Functional relationships*

Where the abiotic (and biotic) driver cannot be measured on the temporal and spatial scales required to adequately characterise the driver, an attempt is usually made to characterise the driver based on a functional relationship between the driver of relevance (*e.g.* nutrient inputs to the marine environment) and factors such as freshwater discharge rate through the estuary mouth, estuarine health (and its influence on nutrient dynamics) and the metocean conditions prevailing both during and following the freshwater discharge into the marine environment.

Functional relationships that may be used to characterise the drivers as follows:

- The **nursery function of estuaries** is determined by the estuarine habitat suitability and the estuarine mouth condition. While the estuarine habitat suitability is not easily quantified, the estuarine mouth condition could be estimated from the flow regime within the estuary (tidal flows and freshwater flows into the estuary) and the prevailing metocean conditions (mainly direct wave effects stirring up sediments that are subsequently transported into and deposited inside the estuary mouth). The tidal forcing and metocean conditions remain more or less the same over the long-term. Freshwater flows to estuaries, therefore, are the only remaining factor by which estuarine mouth dynamics may change. Providing a correlation between freshwater inflows and mouth conditions, however, is not a trivial exercise as each estuary, because of its specific character, has its own correlation between river flow and mouth conditions (Theron and Bergman, 2007). Therefore it is risky to extrapolate functional relationships from one estuary to another (Huizinga, 2002) without an adequate understanding or a validated generic regime-type model to do so.

- The exact nature of the signal giving effect to the **cueing effect** is uncertain, however it is reasonable to assume that the extent and persistence of low salinities (or a similar freshwater related tracer) in marine environments may be a reasonable proxy for determining the magnitude of the cueing effect. It may be that the ecology of the estuary may provide olfactory cues that are somewhat unrelated to the magnitude of the freshwater flows entering the marine environment, but rather whether or not there exists a freshwater flow into the marine environment from the estuary, no matter what its magnitude.

- The **availability of and extent of physical habitat** as defined by the distribution of marine sediments, is determined not only by the quantity but also the quality (*i.e.* grain size, *etc.*) of the sediments being discharged from the estuary. Characterising the quantity and quality of sediments being discharged from an estuary into the marine environment is not a trivial exercise. The quantity and quality of sediment discharges to the marine environment from a particular estuary is a complicated function of conditions in the

catchment, river and estuary, flow variability within the estuary and estuary mouth conditions. Further the initial deposition, re-suspension and final deposition of such sediments (*i.e.* spatial and temporal extent of physical habitats based on sediments) in the marine environments is strongly dependent on the nature of the freshwater flows from estuaries (freshets, floods, *etc*) as well as prevailing metocean conditions.

- **Fronts and other retention mechanisms** include the boundaries between the surf-zone and coastal waters, between freshwater plumes and the surrounding coastal waters and the vertical boundary between low salinity surface plumes and the underlying coastal waters. The existence, extent and persistence of these frontal regions and areas of high water column stability are dependant mainly on the magnitude of the freshwater inflows to the marine environment but also are significantly modified by the prevailing metocean conditions.

- **Nutrient inputs** to the marine environment occur as **dissolved nutrients** and **POM**. The primary factors determining the input of **dissolved nutrients** into the marine environment are a consequence of the nutrient dynamics within each estuary that, in turn, are a complex combination of nutrient input via the river and direct run-off into the estuary, nutrient uptake by primary producers, re-mineralisation within the estuary and interchange with coastal waters. Thus there is unlikely to be a simple relationship between the nutrient concentrations in waters discharged to the marine environment and freshwater flow rates through the estuary (van Ballegooyen and Gulekana, 2005), although Snow and Taljaard (2007) have made significant progress in developing conceptual models of the water quality characteristics (including inorganic nutrients) of temporarily open/closed estuaries in South Africa. Taljaard *et al.* (2007) have further refined those conceptual models in terms of nutrient cycling and transformation processes within the estuary, the intention being to extend those models to other types of estuarine systems. Similarly, the **POM** discharged into the marine environment via an estuary is dependant on conditions in the estuary (such as the health of the estuary and anthropogenic input of nutrients into the estuary) and the nature of the freshwater flows through the estuary. In the simplest of terms, the nutrient loads into the marine environment could be considered to be a function of the particular estuary under consideration and the flow variability within and through the estuary (van Ballegooyen and Gulekana, 2005).

Table 1: Table of the intensity of the functional relationship between the drivers and the variables used to characterise the drivers

Drivers		Variables utilized to characterise drivers							
		Estuarine-specific characteristics			Anthropogenic influences				Metocean conditions (i.e. mainly transport and fate in marine environment)
		Estuarine Morphology	Estuarine Health	Mouth Condition	Nutrient loads into estuary via river run-off and/or groundwater	Reduction in river/estuarine sediments (e.g. by dams)	Reduction in freshwater inflows to the estuary	Reduction in groundwater flows (due to abstraction)	
Nursery function	Estuarine Habitat suitability	2			1 to 2	1 to 2		2 to 3	3
	Mouth Condition					?		2 to 3 ?	
Cueing effect (estuary discharges)			?		?	?		2 to 3	
Nutrient availability	Dissolved Nutrients	2[*1]	1 to 2			?			
	POM	2			2	1 to 2		2?	
Availability and extent of physical habitat: marine sediments	Sediment quantity/ (sediment loads)	2	3						
	Sediment quality (Grain size distribution)	2	3	2					
Turbidity		2	3					?	
Fronts & retention mechanisms	Vertical stratification							3	
	Horizontal fronts							3	
Salinity								2 to 3	
Temperature						3			
Submarine groundwater discharges	Dissolved Nutrients								
	Cueing Effect								
	Salinity								

[*1] The morphology of the estuary influence the residence time in the estuary of river inflows and consequently the potential for the utilization mainly dissolved nutrients in the estuary-.

[*2] There could be a non-anthropogenic source of nutrients in groundwater due to the nitrogen fixing activities of coastal vegetation

	Strong relationship
1 to 2	Moderate to strong relationship

2	Moderate relationship
2 to 3	Moderate to weak relationship

3	Weak relationship
?	Uncertain relationship

- The magnitude, extent and persistence of changes in **water temperature** in the marine environments due to changes in freshwater inflows to the marine environment are determined by the temperature differences between estuarine and coastal waters as well as the prevailing metocean conditions in the marine environment. Unlike salinity, temperature is a much less conservative property of seawater and can be significantly influenced by prevailing atmospheric conditions (*e.g.* wind speed, insulation, cloudiness, relative humidity, air temperature, *etc*).

- The extent and persistence of **low salinity** waters in the marine environment depends primarily on the magnitude of the freshwater flows from rivers and estuaries into the marine environment, but also are significantly modified by the prevailing metocean conditions in the adjacent ocean.

- The extent and persistence of **water column turbidity** depends both on the quantity and quality of sediments being discharged from river and estuaries. The greater the percentage of fines discharged from the estuary, the greater the likely turbidity in the marine environment. Similarly the greater the flows into the marine environment, the more extensive the likely turbidity in the marine environment. Water column turbidity need not be directly related to recent sediment discharges from estuaries but also could be a consequence of the stirring up by storm conditions of previously discharged fines that have accumulated in the marine environment.

The existence, extent and persistence of **dissolved nutrients** (and possibly **low salinity conditions**) in the marine environment due to groundwater discharges depend primarily on the magnitude of the submarine groundwater discharges and the prevailing metocean conditions in the nearshore marine environments.

As noted above, the **metocean conditions** in the marine environment play a major role in determining the exact nature of the drivers. For example:

- Tidal and wave conditions (and associated beach morphology) at or in the vicinity of the estuary mouth are strong determinants of the open or closed state of an estuary mouth;

- metocean conditions, such as wave-driven currents in the nearshore zone play a major role in determining the extent and persistence of elevated nutrient concentrations, reduced salinities, changes in water temperature, elevated turbidity, water column stability and the location, extent and functioning of oceanic fronts. Due to the limited exchange between the surf-zone and deeper waters and the strong alongshore flows that may prevail in the surf-zone, estuarine waters (or groundwater) entering the surf-zone may form narrow zones of low salinity (and possibly nutrient-rich and/or turbid) waters that extend great distances alongshore;

wave and current conditions also determine the distribution and persistence of marine sediments that provide suitable habitats in offshore environments.

The strength of the relationships between the driver and the variables used to characterise these drivers is given in Table 1. A strong functional relationship exists between the drivers and:

- changes in freshwater inflows to the estuary;
- the estuary mouth condition;
- the metocean conditions prevailing in the adjacent marine environment and;
- in the case of submarine groundwater discharges; the magnitude of submarine groundwater discharges and the nutrient concentrations in the groundwater at the point of discharge. The latter is dependant on the nature of the biogeochemical processes and submarine groundwater recharge (see Part I: Section 4.2.1 and Part II: Section 4.1.2 of this report for a description of these processes).

The interrelationship of the various drivers is complex and not adequately reflected in Table 1. For this reason we have attempted to characterise these interrelationship schematically in Figure B.2 (Appendix B). The schematic does not indicate all possible relationships between the drivers and potential ecosystem responses but does capture the most important of these relationships, particularly insofar as they are dependant on changes in freshwater inflows to the marine environment.

In summary, the important abiotic (and biotic) drivers may be characterised in terms of

- access to and quality of relevant habitats;
- quantity and quality of freshwater, nutrient and sediment discharges into the marine environment; and
- the transport and fate of these discharges (*i.e.* the extent and persistence of regions of reduced salinity, increased nutrients, *etc*) in the marine environment that is determined primarily by regional morphology (*e.g.* the existence of coastal embayments) and prevailing metocean conditions.
- in the case of submarine groundwater discharges, the magnitude of submarine groundwater discharges and the nutrient concentrations in the groundwater at the point of discharge, both of which are a function of the nature of the biogeochemical processes and submarine groundwater recharge.

4.5.5 Information requirements

In order to assess the ecological response to abiotic (and biotic) drivers of relevance, appropriate measurements and/or simulations are required to characterise the drivers on the temporal and spatial scales of relevance as described in Part I: Section 4.5.3 above. Furthermore, the biotic response components need to be appropriately measured. For example, a measure such as catch per unit effort is an indicator of abundance that may on occasion fail due to a change in environmental conditions (*e.g.* nearshore turbidity) impacting the biotic response component under consideration and well as catchability. Further, technological advances, increased boat

capacity and increased efficiencies may also bias results based on simple measures of effort such as hours trawled (*e.g.* Demetriades and Forbes, 2003).

The spatial and temporal attributes of such measurement and model outputs are:

- those required to research/define the relationships between abiotic (and biotic) drivers and the ecosystem response, and
- those required to monitor and/or manage marine ecosystems in terms of their freshwater requirements.

The focus here is on the temporal and spatial characteristics of the measurements and model outputs required to research the effect of the reduction of freshwater inflows to the marine environment of South Africa. In Table D.5 in Appendix D, for example, the relevant temporal and spatial scales in terms of the role estuaries and estuarine inputs are listed in the following order:

i) temporal and/or spatial resolution required to adequately characterise the abiotic (and biotic) drivers. These may include direct measurements of the relevant drivers or measurements of other variable that are used to characterise the drivers, *e.g.* the resolution of flow rates and nutrient concentrations in estuarine outflows needed to characterise nutrient loads into the marine environment.

ii) the duration and spatial scale of aggregation/integration of the driver signals required to assess the biotic response, *i.e.* the integration of drivers on temporal and spatial scales similar to the biological response times and spatial scales over which this biological response occurs.

iii) The minimum period over which a significant biotic response can be expected (Table D.5).

The results from the workshop indicate that:

- ideally daily measurements or estimates are required of the drivers (or proxy variables used to characterise the drivers),
- that these measurements as a minimum need to be able to resolve event-scale variability[25], and
- that generally multi-year time series are required to develop robust relationships between parameters typically measured to characterise:
  - the drivers of relevance (*e.g.* functional relationships between freshwater flows and nutrient loads into the marine environment);

[25] In estuaries event scale variability implies major flow events (e.g. morphology "resetting" flood return periods may be in the order of 50 to 100 years). In the marine environment event-scale variability in terms of water column and water quality processes is primarily characterised by synoptic weather events (e.g. ranging form 3 to 10 days), while variability in terms of sediment processes (sediment deposition and turbidity events) is typically longer and it related to significant storm events (*i.e.* a couple of times a month to once yearly or longer, depending on the location under investigation).

– the relationships between the various drivers and relevant ecosystem response components.

The exact nature of the measurements required will depend on the nature of analysis deemed appropriate for the region under consideration (*e.g.* regional assessment for the Natal Bight, coastal embayment-scales assessments for the south-eastern Cape coast and nodal assessments for the West Coast.).

Once information requirements have been specified, a gap analysis should be undertaken to determine which of these data exist and which of these data still need to be measured. Depending on the costs involved and the resources available for the assessment, it may be necessary to deviate from the idealised assessment framework described above.

In attempting to fill the identified data gaps, both existing and new technologies (satellite remote sensing, numerical modelling, *etc*) need to be considered. Furthermore, (both local and international) research programs and funding sources that can contribute to the assessment of the freshwater requirements of the marine environment need to be identified.

4.5.6 Appropriate assessment methods

The assessment method or technique (*e.g.* correlation analyses, numerical modelling, Bayesian networks, *etc*) selected needs to be consistent with the quantity and quality of the data and other information available, the existing understanding of the ecosystem and the resources allocated for the assessment. The assessment method selected therefore is expected to be influenced by:

- the management and environmental quality objectives,
- the ecosystem extent (*i.e.* biogeographic region of interest),
- the keystone and/or indicator species selected for assessment,
- the key abiotic (and biotic) drivers identified and the availability of data to adequately characterise these drivers, and
- existing knowledge of the ecosystem response to the key abiotic (and biotic) drivers.

Two broad approaches[26] to assessing the potential impacts of a reduction in freshwater flow into estuarine and marine environments are common in the literature:

- a **"correlation" approach** in which the effects of freshwater on the abundance, biomass or diversity of organisms are analysed statistically (*e.g.* Thukela study, Louw, 2003) with a lesser focus on detail of the physical and ecological processes involved. This approach allows for a correlation to be developed between the biotic response and both basic

26 Both approaches are based on the concept of a driver-response model, whereby an attempt is made to quantify the ecological response to one or more abiotic (or at times biotic) drivers such as, for example, nutrient inputs into the marine environment.

abiotic drivers (*i.e.* drivers such as nutrients, sediment loads, *etc*) and/or indirect measures such as flows through the estuary mouth that can be used to characterise or act as a proxy for the abiotic drivers.

Where there is a better understanding of the ecosystem or the life cycle of the keystone species, a similar correlation approach may be undertaken but with a certain amount of "intelligence" being incorporated into the independent regression variables, *i.e.* a number of basic measures of abiotic drivers can be combined in a manner that provides an environmental index or indices considered to better represent the life-cycle and habitat requirements of the keystone species under consideration. This approach was successfully undertaken for the KwaZulu-Natal prawn fishery in the Thukela study (Louw, 2003) that was based on more extensive data sets[27] that provided a reasonable understanding of the physical and ecological processes involved.

- at the other extreme is **a process-orientated approach** (*e.g.* a more quantitative driver-response approach) where the more basic drivers are measured or modelled and aggregated at appropriate temporal and spatial scales to provide the requisite input into detailed ecosystem or individual-based response models in which there is a greater consideration of the exact nature of the processes involved. These models allow for a better understanding the function and impact of freshwater input into marine systems and a more robust predictive capability to be developed (*e.g.* the Catchment-to-Coast study of the Maputo Bay ecosystem - Monteiro and Matthews, 2003; Louw, 2003; Gillanders and Kingsford, 2002).

  For example, in such an approach the focus would not only be on sediments and nutrient fluxes into the coastal and offshore environments but also how these nutrients and sediments fluxes or loads are distributed and utilized in these environments (*i.e.* the nature and persistence of the various habitats[28] that may be created or maintained). This information typically would be required by the more detailed ecosystem and/or individual-based models utilized in this approach to develop a more robust predictive capability. Numerical modelling plays a major role in such a process-orientated approach[29], however, depending on the level of sophistication of the modelling effort, this may be quite costly and require a large amount of project resources.

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27 The analysis and conclusions of this study were based on 20 years of estuarine and offshore catch data, 20 or more years of St Lucia salinity data including droughts and cyclones, monitoring of postlarval recruitment into Kosi, St Lucia, Richards Bay and Durban Bay, assessment of the viability of the St Lucia and Richards Bay bait fisheries, growth experiments in the field, tagging studies in St Lucia and Richards Bay with subsequent monitoring of the recoveries of trawlers and physiological studies of temperature and salinity responses in the laboratory.

28 In this report the habitat is understood to be a broader definition than simply a physical habitats comprising sediment grain size, macrophytes, *etc* and includes considerations such as required salinity and nutrients regime, availability of nursery areas, etc.

29 Fairly extensive use has been made of numerical modelling in assessing the potential impacts of the reduction in freshwater inflows to South African estuarine systems, particularly where there is a complex response to such freshwater inflows to an estuary (*e.g.* Bate and Adams, 2000; van Ballegooyen *et al.*, 2004).

The essential difference between the two approaches is in the degree and manner in which the measures of the assumed abiotic and biotic drivers are aggregated prior to being utilised in the keystone species, ecosystem or social-economic response models.

In using the former **"correlation" approach** there is a greater reliance on specialist expertise and less on measured or derived (*e.g.* modelled) time series. The specialist expertise is typically incorporated into the correlation indices utilized in the statistical analyses. Any subjectivity that exists in this approach is introduced mainly via the correlation indices utilized and not the quantitative statistical techniques chosen for the analyses. Such an approach is characteristic of exploratory studies or preliminary assessments where there is limited available data and limited resources both for obtaining additional measurements and for the assessment itself. This approach has the advantage of providing rapid results with minimal resources, however it typically provides results of only limited confidence and it is possible for the assessment process to be biased by subjective opinions of one or more of the specialists involved.

Furthermore, the use of correlation or regression analyses to identify environmental variables contributing to variation in, for example fisheries catches, can be criticised (Robins *et al.*, 2005) due to the fact that:

- the relationships between, for example, fisheries catches and freshwater flow (or rainfall) are potentially confounded by other factors such as fishing effort and spawning stock size (*e.g.* da Silva 1985), their degree of influence depending on the extent of exploitation of the population by the fishery (Vance *et al.* 1985). Despite this, most of the correlative studies do not explicitly account for these factors.
- the potential and likely non-linearity of causative mechanisms and the likelihood of multiple causative mechanisms;
- the possibility of type I errors (*i.e.* false significant correlations);
- the lack of ability to prove causality (*i.e.* a correlation indicates causality but does not prove causality).

The Thukela study (Louw, 2003) was based on such a "correlation" approach, however in the assessment of potential impacts on the prawn fishery, additional "intelligence" was incorporated into the independent regression variables used in the correlations with prawn catches. The Thukela study, including prior specialist studies, cost approximately R 1 million (2003).

The alternative approach, a highly **process-orientated approach**, typically requires significantly greater input data and resources to undertake an assessment. In this approach the specialist expertise is incorporated mostly in the specialist models utilised to characterise the various abiotic and biotic domains (*e.g.* hydrodynamic modelling, water quality modelling, individual-based models), as well as the manner in which the results from the various models are aggregated when linking the various specialist models. Consequently, any subjectivity that exists in this approach is introduced via the extent and nature of the processes that are incorporated into the various specialist models and in the manner of aggregation of data when linking the models (*i.e.* the

temporal and spatial characteristics of aggregation). This approach is likely to provide results of a much higher confidence and a more robust predictive capability. There is also less opportunity for introducing bias by subjective opinions that may be held by one or more specialists. Overall the process is more objective but requires significantly greater resources and takes longer to complete. Such an approach requires that there exists sound knowledge of the ecosystem being studied and that the relationships between the abiotic and biotic components of the system have been well-quantified. This is the approach taken in the Catchment-to-Coast study of the Maputo Bay ecosystem (Monteiro and Matthews, 2003) that conservatively is estimated to have cost approximately 2.5 million Euros (2005), including resources and services provided by the participating institutions.

Both approaches *have an uncertain predictive capability as a consequence of long-term climatic variation or other human-induced changes* (*e.g.*, habitat reduction, increased pollution, impacts of fishing, *etc*). For example, global climate modelling suggests that the eastern seaboard of Africa is likely to get more rainfall in the future (Hewitson and Crane, 2006). This is likely to change run-off characteristics along the KwaZulu-Natal coastline. Similarly, the very act of the exploitation of living marine resources, that provides the data required to assess the role of freshwater inflows on marine ecosystems, is likely to be a severe limitation to the assessment of changes in freshwater inflows to marine environments and result in a limited predictive capability.

Both approaches, however, are suited to developing adaptive management strategies using methods such as Bayesian networks[30] (*e.g.* Peters *et al.*, 2007), albeit at different cost and inherent levels of uncertainty.

However, given the paucity of data and the preliminary nature of the assessment being attempted here, neither of these approaches has been strictly followed. The assessment here (Part II; Section 7) rather comprises a review mainly of existing published and unpublished data.

4.5.7 Integration

Given the potential for a number of management and environment resource quality objectives, it is likely that any assessment will need consider a range of keystone and indicator species. To obtain a holistic assessment of the effects of changes in freshwater inflow to marine environment requires the integration of the results for the various keystone and indicator species analyses. Based on this integrated outcome, decisions can be made as to the acceptability the physical and ecological changes predicted to occur in response to the reduction of freshwater inflows to the marine environment.

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[30] An assessment approach that encapsulates the strengths of both of the above approaches is that of a Bayesian network. The particular advantages of the Bayesian network approach is its ability to handle different levels of information confidence in the relationships between the various components of the network of biophysical interactions and the ability to explicitly handle uncertainties in these relationships.

4.5.8 *Recommendations for future studies*

Should there remain significant uncertainty in such an integrated assessment, it may be that additional measurements and studies need to be undertaken before the assessment is considered sufficiently robust to make recommendations on specific freshwater requirements for a particular ecosystem. Recommendations for ensuring a more robust assessment of the potential freshwater requirements of South African marine ecosystems are provided in Part II: Section 9 of this report.

4.6 Recommended Freshwater Requirements

Should changes in freshwater flow result in significant impact on a marine ecosystem, to meet the management and environmental quality objectives for the marine ecosystem, a minimum freshwater flow will need to be recommended, *i.e.* a quantity of freshwater analogous to the ecological reserve often specified for estuarine environments. It will need to be assessed whether the recommended quantity of freshwater to be "reserved" for the marine ecosystem is acceptable to all stakeholders.

4.7 Evaluation of Socio-economic Importance

Before decisions can be made as to the acceptability of the physical and ecological changes predicted to occur in response to the reduction of freshwater inflows to the marine environment, it is necessary to link the outcomes of the assessment to the socio-economic implications of the potential changes. This is an importance process as in the absence of other strong mandates (*e.g.* mandates associated with legislation or treaties, *etc*), it is on this basis that decisions are likely to be made. Note that there should have been some preliminary assessment of socio-economic issues when selecting appropriate keystone and indicator species for the initial assessment.

The assessment of socio-economic issues is not trivial. For example, line fisheries are important in both a true commercial sense but also in a socio-economic and political context where issues such as subsistence and artisanal fishing, sustainable livelihoods, poverty alleviation and biophysical resource security are of importance. A specific change in such a fishery is likely to have widely disparate outcomes. For example, a moderate increase in catch per unit effort (CPUE) in the line fishery is not likely to have a significant impact on the recreational line fishery and its associated benefits to the local economy. It is likely that such a moderate increase in CPUE will have little effect on the extent of activity in the recreational line fishery. However, such a moderate change in CPUE is expected to have a significant impact on subsistence and artisanal fishing where the benefits are directly related to the level of CPUE (*i.e.* it is of direct relevance to a subsistence fisher that an increased effort is required to achieve the same protein intake).

Similarly, setting a requirement for freshwater flows into estuaries and coastal marine ecosystems is likely to have significant opportunity costs in the catchment in terms of limitations on the use of freshwater both for potable use and agriculture.

A formal methodology is being developed under CSIR leadership whereby the various "trade-offs", occasioned by developments resulting in changes in the utilization of natural resources of a region, can be decided upon based on comparisons of the various development options proposed by using a common measure or "currency", *i.e.* total economic value (Peters *et al.*, 2007).

Based on the outcome of an assessment of socio-economic consequences of a recommended freshwater requirement for the marine environment, freshwater flow scenarios other than those recommended may need to be assessed. Such a re-assessment results in a potential feed-back loop in the proposed assessment framework whereby the scientific assessment studies will need to be repeated and possibly even the management and environmental quality objectives reconsidered, should the changes or constraints be such that this is required.

4.8 Allocated Freshwater Requirements

Only once the recommended freshwater requirements have been assessed and found to be acceptable to all (or the majority) of stakeholders is it likely that the recommended freshwater requirements will become "allocated" freshwater requirements to which there will need to be compliance.

Given the likely residual uncertainties in the scientific assessment an adaptive management approach is best implemented whereby, as more knowledge is gained of these marine ecosystems, the allocated freshwater requirements are amended accordingly to ensure optimal sustainable utilisation of these ecosystems.

PART II

AN INITIAL ASSESSMENT OF THE ROLE OF FRESHWATER IN SOUTH AFRICAN MARINE ECOSYSTEMS

1. Introduction

The approach used in undertaking this preliminary assessment of the freshwater requirements of the marine environment of South Africa is largely based on the framework proposed in Part I of this report, but differs in a few key aspects:

- to avoid the potentially iterative process of selecting an ecosystem extent (biogeographical domain) of interest and keystone species of relevance in this domain, we *a priori* have separated the marine environment into biogeographic domains.
- the selection of appropriate keystone and/or indicator species was informed by both the initial workshop and subsequent discussions with the workshop participants, however there was a level of expediency in the selection of the keystone or indicator species based on the availability of existing studies and appropriate data for the assessment of the ecological response to reduced freshwater inflows to coastal ecosystems.

Furthermore, no attempt has been made to recommend potential freshwater requirements for South African marine environments due to the large uncertainties that remain. The focus here rather has been on understanding the likely role of freshwater in the marine requirements and characterising this role as best possible using available literature and existing data.

A preliminary assessment of the freshwater requirements of the marine environment of South Africa follows, whereby the key components of the assessment framework are addressed.

2. Legislation and Policies

In setting management and environmental quality objectives for the marine environment with respect to potential freshwater reduction requires that South Africa's international obligations, policies and legislation need to be taken into account.

International conventions and treaties of relevance for South Africa include:

- Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA) (1995);
- United Nations Convention on Biological Diversity (1992);
- Agenda 21 (1992);
- United Nations Framework Convention on Climate Change (1992);
- Convention on the Protection, Management and Development of the Marine and Coastal Environment of the East African region (Nairobi Convention) (1985);
- Convention on the Protection, Management and Development of the Marine and Coastal Environment of the West and central African region (Abidjan Convention) (1981);
- United Nations Environmental Programme (UNEP) (1972).

In addition, the principles and policies that should be considered include:

- White Paper on the Development and Promotion of Tourism in South Africa (May 1996);
- White Paper on Water Policy in South Africa (April 1997);
- White Paper on a Marine Fisheries Policy for South Africa (May 1997);
- White Paper on Sustainable use of South Africa's Biological diversity (May 1997);
- White Paper on Environmental Policy (July 1997);
- White Paper for Sustainable Coastal Development in South Africa (April 2000).

National legislation to be considered in setting management objectives for the marine environment includes:

- Constitution of South Africa
- National Environmental Management Act 107 of 1998 (NEMA)
- National Water Act 36 of 1998
- Marine Living Resources Act 18 of 1998
- Environmental Conservation Act 73 of 1989
- National Environmental Management: Biodiversity Act 10 of 2003
- National Environmental Management: Protected Areas Act 57 of 2003
- National Environmental Management: Integrated Coastal Management Bill.

Here the National Water Act (Act 36 of 1998) is of particular importance as it calls for integrated management of water resources on an ecosystem basis. The Act prescribes a two-tier approach to the development of water resource management strategies, the **National Water Resources Strategy** (NWRS) and the **Catchment Management Strategy** (CMS). The NWRS sets out the macro-framework within which South African water resources must be managed. Catchment management agencies on the other hand, are responsible for the preparation of a CMS within their particular area of jurisdiction.

The National Water Act also provides for the integration of water resource management and co-operative governance via the NWRS. The latter sets a framework for water resource management, which includes the two-prong approach of **Resource Directed Measures** (*e.g.* for the management of rivers, wetlands, estuaries and groundwater) and **Source Directed Measures** (*e.g.* recycling, reduction in water use).

A significant omission of the national Water Act is that it **does not define the marine environment as a water resource**. As a result, the protection given to water resources such as estuaries does not apply to marine waters. As noted in Part I of this report, the marine environment often depends on inputs of nutrients and sediments from rivers and estuaries, *i.e.* it also has a "Reserve" for freshwater in terms of water quantity and quality. Furthermore, the marine environment and estuaries are strongly linked in terms of their ecological functioning, *e.g.* there are a number of marine species that have an estuarine phase in their life cycle. Therefore, if the state of estuarine environments deteriorate due to changes in freshwater inputs to these environments, the state of the adjacent coastal and offshore waters is also likely to deteriorate.

Similarly, a deteriorating marine environment adjacent to estuaries is likely to result in less healthy estuarine environments.

In Part I of this report, the proposed framework for the assessment and management (in terms of potential freshwater requirements) of the South African marine environment as a water resource, assumes that the above deficiencies of the legislation will be resolved.

A brief overview of the approach of **Resource Directed Measures** used for the management of rivers, wetlands, estuaries and groundwater follows as it is likely to provide a good starting point for developing a specific framework to assess potential impacts of freshwater reduction on the coastal and marine environment of South Africa (DWAF, 2004).

Resource Directed Measures incorporate the following concepts:

- The **Reserve** (the basic human needs reserve and the ecological reserve);
- **Resource Quality Objectives** (Management objectives)
- The "class" of the water body being managed (condition or health status).

The Reserve consists of two parts – the Basic Human Needs Reserve and the Ecological Reserve. The basic needs reserve provides for the essential needs of individuals served by the water resource in question and includes potable water and water required for the preparation of food. The **Ecological Reserve** relates to the amount of water required to protect the aquatic ecosystems of the water resource. The Reserve refers both to the **quantity** and **quality of the water** in the resource, and will vary depending on the class of the resource. The DWAF is required to determine the Reserve for all or part of any significant water resource.

There are **various levels of reserve determination** that can be undertaken: ***desktop, rapid, intermediate and comprehensive determinations***. The first two categories take little time, require a small amount of data and involve a cheap and expeditious process. However, only limited confidence can be placed in the results and it follows that a reserve determination undertaken by either the desktop or rapid method must be approached conservatively. On the other hand, the intermediate and comprehensive determinations take longer, are more expensive, and involve more data collection and greater stakeholder participation. It follows that the results of intermediate and comprehensive reserve determination can be used with more confidence.

A generic method has been developed for the different levels of reserve determination. Protocols based on this approach also take into account factors such as the sensitivity of a water resource to flow reductions, and its importance in terms of various criteria (*e.g.* maintenance of biodiversity, *etc*).

The proposed assessment framework used here for assessing the importance of and managing changes in freshwater (and sediment) inflows to South African marine ecosystems is based on a similar approach to the **Resource Directed Measures** used for the management of rivers, wetlands, estuaries and groundwater. However, the significant differences between the river,

wetland, estuarine and groundwater environments and the marine environments (*e.g.* there is no requirement for a "Basic Human Needs Reserve" for the marine environments, the ecosystem extent is more difficult to define, *etc*), have meant that there have been some significant modifications to the Resource Directed Measures approach.

The relevance and implications of the other legislation listed above, is summarised in Appendix A. To ensure the effective implementation of policy and legislation on a national level for the marine environment it is crucial that these, together with other mandated priorities of the country such as job creation, poverty alleviation, socio-economic equity and biophysical resource security, be translated into sound management objectives/strategies.

Of potential concern is the fact that there presently exists jurisdictional fragmentation in South Africa, whereby the Department of Water Affairs (DWAF) is largely responsible for managing upstream activities while the Department of Environment Affairs and Tourism (DEAT) is the dominant role-player in managing marine ecosystems. This could lead to conflict or, worse, a situation where neither department takes responsibility for ensuring that the freshwater requirements of the marine environments are adequately managed.

3. Management and Environmental Quality Objectives

While the specific management and environmental quality objectives may vary from region to region, it is expected that the assessment and management framework to be used nationally would need to have specific goals in mind and a consistent philosophy in terms of the broad management objectives of relevance. This specifically implies the harmonisation of management objective/strategies between national departments (particularly DWAF and DEAT) and, where transboundary issues are of relevance, between the appropriate national departments of the countries involved.

The management and environmental quality objectives need to take into account the following legislatively mandated principles:

- secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development' (*Constitution of South Africa*);
- specific protection of sensitive, vulnerable, highly dynamic or stressed ecosystems, such as coastal shores, estuaries, wetlands and similar systems (*National Environmental Management Act*);
- the management of Marine Living Resources according to the following principles (*Marine Living Resources Act*)
  - optimum utilisation and ecologically sustainable development of marine living resources;
  - conservation of marine living resources for both present and future generations;

- applying a precautionary approach in respect of the management and development of marine living resources;
- utilising marine living resources to achieve economic growth and human resource development;
- capacity building within fisheries and mariculture and employment creation;
- protection of the ecosystem as a whole, including species which are not targeted for exploitation;
- preservation of marine biodiversity;
- broad and accountable participation in the decision-making processes;

- the protection of water resources according to the principles of maintaining ecosystem function and integrity and biodiversity principles (*National Water Act 36 of 1998* – note that presently this act does not apply to the marine environment as marine waters are not defined as resource by this Act, *i.e.* in terms of coastal ecosystems, applies only to estuaries);

- promote sustainable livelihoods for local communities and conserve, protect or enhance coastal ecosystems of biodiversity in the area (*Marine Living Resources Act* and *National Environmental Management: Integrated Coastal Management Bill*);

- the effective management of biodiversity and the components of biodiversity in the region, including rare and endangered species (*National Environmental Management: Biodiversity Act 10 of 2003*);

- Appropriate management of protected areas, in this case specifically marine protected areas, by adequately protecting ecologically viable areas representative of South Africa's biological diversity according to the following principles (*National Environmental Management: Protected Areas Act 57 of 2003*)
  - preservation of the ecological integrity;
  - conservation of biodiversity;
  - protection of South Africa's threatened or rare species;
  - protection of vulnerable or ecologically sensitive areas
  - ensure sustainability of environmental goods and services and to provide for the sustainable use of natural and biological resources
  - creation or augmentation of destinations for nature based tourism;
  - to manage the interrelationship between natural environmental biodiversity, human settlement and economic development; or
  - generally, to contribute to human, social, cultural, spiritual and economic development.

- obligation of the national government in terms of any international agreement or international law (*e.g.* biodiversity, etc).

In estuaries, the management and environmental quality objectives are more clearly defined by attempting to manage each estuary according to a management class that takes into account issues such as the present ecological status (PES) and an estuary importance index. The present ecological status sets the minimum Ecological Category, while the degree to which the Ecological Category needs to be elevated higher than the present ecological status depends on level of importance and level of protection or desired protection of a particular estuary (DWAF, 2004).

In summary, management and environmental quality objectives are therefore required that ensure:

- adequate protection of marine living resources, especially those subject to important socio-economic activities;
- adequate protection of coastal an offshore environments utilised for socio-economically important activities such as recreation and tourism;
- maintenance of ecosystem function and integrity of marine systems, particularly in marine protected areas;
- maintenance of biodiversity and adequate protection of rare and endangered species in marine systems.

In marine environments, the implementation of these management objectives requires the adoption of an appropriate management approach and, based on resource utilization in the region of interest, the specification of appropriate Environmental Quality Objectives. These Environmental Quality Objectives need to be translated into measurable specifications or target values and are the marine environment's counterpart of the Resource Quality Objectives in the RDM process undertaken for estuaries.

For this preliminary assessment, we have not defined such clearly quantifiable specifications or target values. The purpose of the initial assessment is more to highlight the potential effects of the reduction of freshwater inflows to the marine environment and provide an initial qualitative (and wherever possible quantitative) assessment of these effects, rather than to provide a definitive and robust quantification of these effects. In that sense, a requirement that "the functioning and integrity of ecosystems is not significantly modified by changes in freshwater inflows to the marine environment", is considered to be adequate for the purposes of this assessment. Such a broad objective is consistent with all of the management and environmental quality objectives listed above. Furthermore, to develop appropriate and comprehensive Environmental Quality Objectives for the different regions requires stakeholder participation and such stakeholder participation is beyond the scope of this project. However, future assessments will require that appropriate Environmental Quality Objectives are defined. In particular, biodiversity issues will need to be more explicitly considered.

4. Ecosystem Definition

It was realised during the initial two day workshop that the preliminary initial assessment of the freshwater requirements of the South African marine environment could be significantly simplified by an *a priori* definition of the ecosystem extent, primarily based on:

- the nature of the freshwater flows (*i.e.* surface runoff and submarine groundwater discharges) into the marine environment;
- the prevailing metocean conditions of the marine environment (*i.e.* physico-chemical classification of the coastal and offshore domain in terms of retention zones, *etc*);
- the distribution of marine biota (*i.e.* biogeographic classification of coastal and offshore oceanographic environments).

4.1 Nature of freshwater inflow

4.1.1 Surface runoff

Freshwater run-off depends primarily on climate and the physical characteristics of the catchments. The rainfall in the different biogeographic regions in South Africa (see Figure 8) can be characterised as follows. The cool-temperate west and southwest coast region comprises either an arid or predominantly winter (moderate to low) rainfall region, the warm-temperate region is a bimodal or year-round, moderately low rainfall region (except for the Tsitsikama region where the moderately high rainfall occurs year round), while the subtropical region is characterised by a relatively high rainfall along the southeast coast region and a slightly lower rainfall along the east coast (Day, 1981), most of which is summer rainfall. The nature and magnitude of the inflows to the marine environment from estuaries will depend on the specific nature of the estuary or estuaries under consideration. For the purposes of this preliminary study it would be useful to classify estuaries according to a broad physical classifications in Table 2 (from Whitfield, 1992 as reported in Taljaard *et al.*, 2003) as well as in terms of their mean monthly flows and mean annual run-off (Turpie, 2004).

While the above rough classification system for estuaries does provide some common characteristics for the various estuaries, there are still large differences in abiotic and biotic characteristics and processes amongst estuaries within a similar category and/or biogeographical region, *e.g.* in terms of natural mean annual run-off, size of the estuary, wave action in the mouth, biogeochemical characteristics of the catchment and adjacent marine environment and biotic composition. Classifying estuaries in terms of their freshwater, nutrient and sediment inputs into the marine environment will remain a challenge and perhaps cannot be achieved with confidence (van Ballegooyen and Gulekana, 2005).

Table 2: Distribution of estuary types in the three biogeographical regions of South Africa (Whitfield, 1992)

ESTUARY TYPE	*BIOGEOGRAPHICAL REGION*		
	COOL TEMPERATE	*WARM TEMPERATE*	*SUBTROPICAL*
Estuarine bay	*0*	*1*	*3*
Permanently open estuary	*2*	*29*	*16*
Estuarine lake	*0*	*4*	*4*
Temporarily open/closed estuary	*5*	*86*	*94*
Modified or canalised estuary	*1*	*2*	*0*
River mouth	*2*	*6*	*4*

4.1.2 Submarine groundwater discharges (SGD)

Submarine groundwater discharges depend on the geology of the region and well as the rainfall patterns. In South Africa the submarine groundwater discharges originate as follows. Primary aquifers typically comprise unconsolidated material or finely fractured terrains (*e.g.* finely fractured Table Mountain Group) that normally result in diffuse groundwater inflows to the marine environment, while secondary aquifers typically comprise fractured rock and are associated with discrete groundwater inflows into the marine environment (*e.g.* submarine springs). Similar discrete groundwater inflows are associated with alluvial groundwater discharges associated with ephemeral river systems (*e.g.* Groen and Spoeg Rivers). SGD's would also be expected to be associated with submarine canyons.

A rough characterisation of submarine groundwater discharges into the marine environment of South Africa may be achieved by mapping hydrogeological terrains/lithographies and combining this information with recharge rates and coastal rainfall zonations. A 1: 1 000 000 scale mapping of principle lithologies has been undertaken (Figure 4) and broad classes of aquifer defined (Colvin *et al.*, 2003, 2006).

Given that the nature of the potential groundwater inflows also is dependant on recharge characteristics determined primarily by the prevailing rainfall regimes, a brief description of the rainfall regimes along the South African coastline follows.

The coastal region north of Cape Columbine is arid and has a rainfall of < 300 mm per annum while the Western Cape between Cape Columbine and Cape Agulhas has a predominantly winter rainfall of approximately 400 to 700 mm per annum (Heydoorn and Tinley, 1980; Day, 1981). From Cape Agulhas to East London the rainfall decreases to approximately 500 mm per annum and is bimodal (with peaks in late summer/early autumn and spring) or occurs almost equally in all seasons (Heydoorn and Tinley, 1980; Day, 1981). The Tsitsikamma region west of Port Elizabeth, comprises a distinct sub-region with a year round rainfall of approximately 700 to 1000 mm per annum. The Eastern Cape Region, between the Great Kei River to Port Edward, receives a predominantly summer rainfall of 800 to 1250 mm per annum. The KwaZulu-Natal

Province, from Port Edward northwards to Kosi Bay, receives a predominantly summer rainfall exceeding 1000 mm per annum.

Thus the coastal region of South Africa can be classified as follows:

- the *cool-temperate west and southwest coast region* comprising either an arid or predominantly winter (moderate to low) rainfall region;
- the *warm-temperate region* that is a bimodal or year-round, moderately low rainfall region (except for the Tsitsikama region where the moderately high rainfall occurs year round);
- the *subtropical region* that is characterised by a relatively high rainfall along the southeast coast region and a slightly lower rainfall along the east coast (Day, 1981), most of which is summer rainfall.

Based on these broad classes of aquifers and rainfall we have provided a rough characterisation of the likely groundwater flows into the marine environment (Figure 4 and Table 3). Note that the characterisation is intended to be indicative rather than definitive.

The classification of biogeographic domains according to submarine groundwater discharges roughly agrees with those proposed above (see Figure 8), the only major difference being the existence of distinct intermediate or transitional zones between the three coastal biogeographical regions proposed.

Table 3: Rough characterisation of groundwater discharges to the marine environment.

ID	BIOGEOGRAPHIC ZONE	GROUNDWATER DISCHARGE CHARACTERISTICS
1	Cool temperate	Predominantly alluvial groundwater discharges at mouths of ephemeral river systems
2		Diffuse surficial groundwater discharges through unconsolidated sediments – winter recharge
3	Intermediate zone	Predominantly discrete discharges (TMG* and $CaCo_3$) – winter recharge
4	Warm temperate	Predominantly discrete discharges – year round recharge
5		Predominantly surficial diffuse discharge – bimodal recharge
6	Intermediate zone	Predominantly surficial diffuse with deeper discrete groundwater discharges – weakly bimodal recharge
7	Subtropical	Surficial diffuse with deeper discrete groundwater discharges – weakly bimodal to summer recharge
8		Surficial diffuse with deeper discrete groundwater discharges – summer recharge

* TMG = Table Mountain Group

The greatest impact of submarine groundwater discharge on marine ecosystems is expected to occur in those areas where the ratio of the submarine groundwater discharge to the surface water run-off is higher than normal and/or where seasonal changes in run-off are large and the submarine groundwater discharge provides a steady inflow during the dry periods. Ecological responses to groundwater inputs to the marine environment are likely to be a consequence of increased nutrient availability in the marine environment, changes in salinity and potential cueing effects associated with groundwater.

The role of submarine groundwater discharges in supplying nutrients to the marine environment in the different regions depends on the potential inorganic dissolved nutrient concentrations and the rate of inflow of the submarine groundwater discharges to the marine environment, as well as the prevailing oceanographic conditions. The National Groundwater Quality Assessment at a National Scale in the Republic of South Africa electronic atlas (WRC, 2000), whilst focussed on groundwater as water resource for human consumption, agriculture and industry, gives an indication of the potential nutrient loads of submarine groundwater discharges.

Primary production in the nearshore zone is most likely to be limited with respect to nitrogen, however on the West Coast, on occasion, silicates may be limiting[31]. The most relevant nutrient loads in the marine environment thus are likely to be nitrates and silicates (Figures 5 and 6).

The National Groundwater Quality Assessment at a National Scale in the Republic of South Africa electronic atlas provides data on nitrates and silicates in groundwater, however the lowest reported concentrations for nitrogen mapped in the electronic atlas are 2 mg/l (143 μM/ℓ)[32] that is some one to two orders of magnitude greater than the mean concentration of NO_3-N of approximately 2,9 to 3,5 to μM observed on the Natal Bight (Carter and d'Aubrey, 1988; Meyer *et al.*, 2002; van Ballegooyen *et al.*, 2003) and the approximately 1,8 μM observed in the nearshore zone. This implies that the Department of Water Affairs and Forestry's water quality database for groundwater will need to be accessed directly to determine potential loads of N into the marine environment. Similarly the minimum reported SiO_2 concentrations in the electronic atlas are one to two orders of magnitude larger than the mean SiO_2-Si concentration of approximately 3,5 μM reported for the Natal Bight.

The concentrations of NO_3 and SiO_2 measured at coastal sites are at best indicative of the potential nutrient loads entering the marine environment due to the biogeochemical transformations that are likely to take place before discharge into the marine environment (UNESCO, 2004) as well as the dilution of the groundwater with seawater that typically takes place before discharge into the marine environment

31 Only likely to occur on the West Coast where diatom blooms are often observed as a result of upwelling.

32 1 μM N ≈ 14 μg/ℓ N and 1 μM Si ≈ 28 μg/ℓ Si

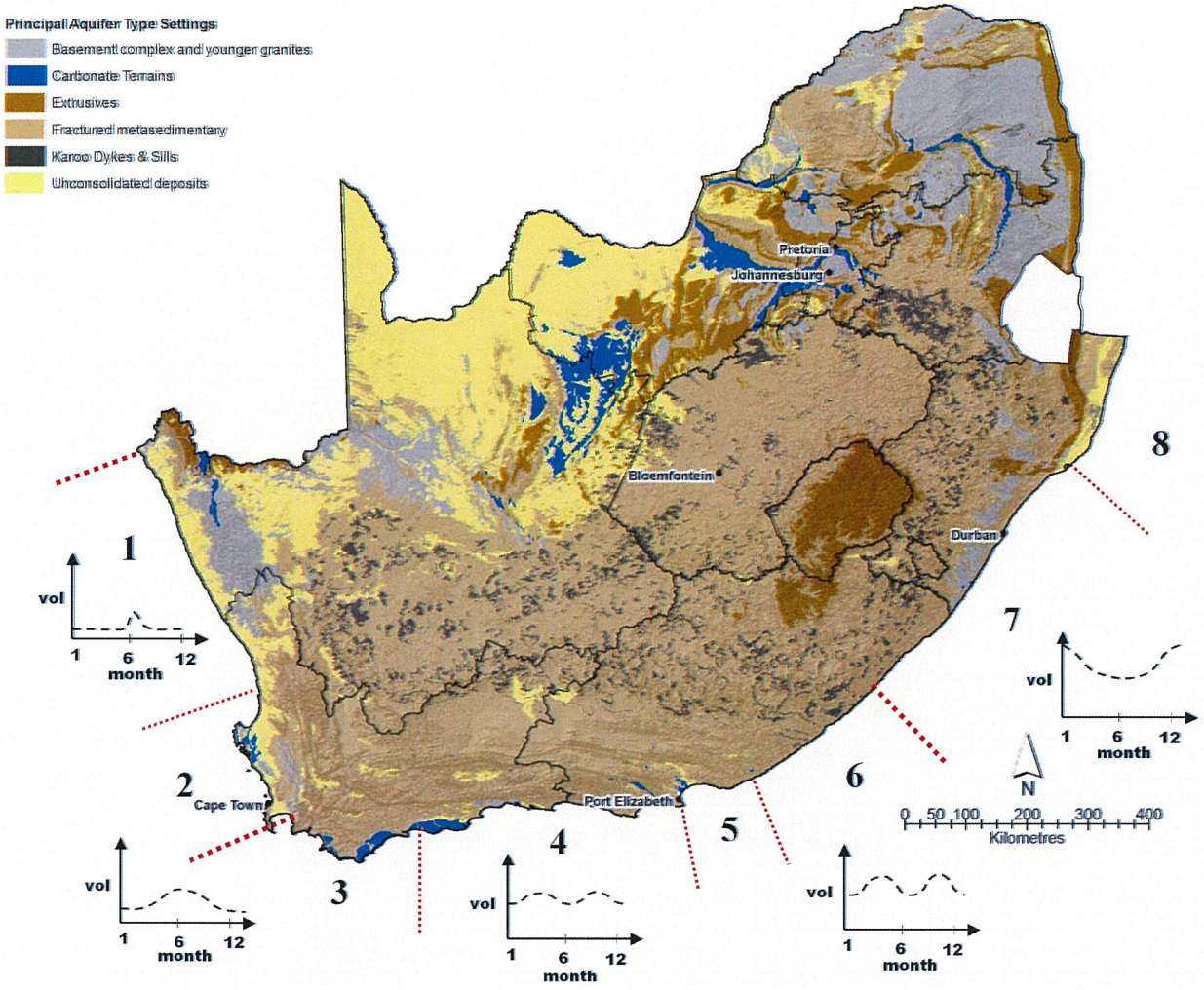


Figure 4: Rough zonation/classification of potential groundwater discharges to the marine environment (See Table 3). The base map is from Colvin *et al.* (2006)

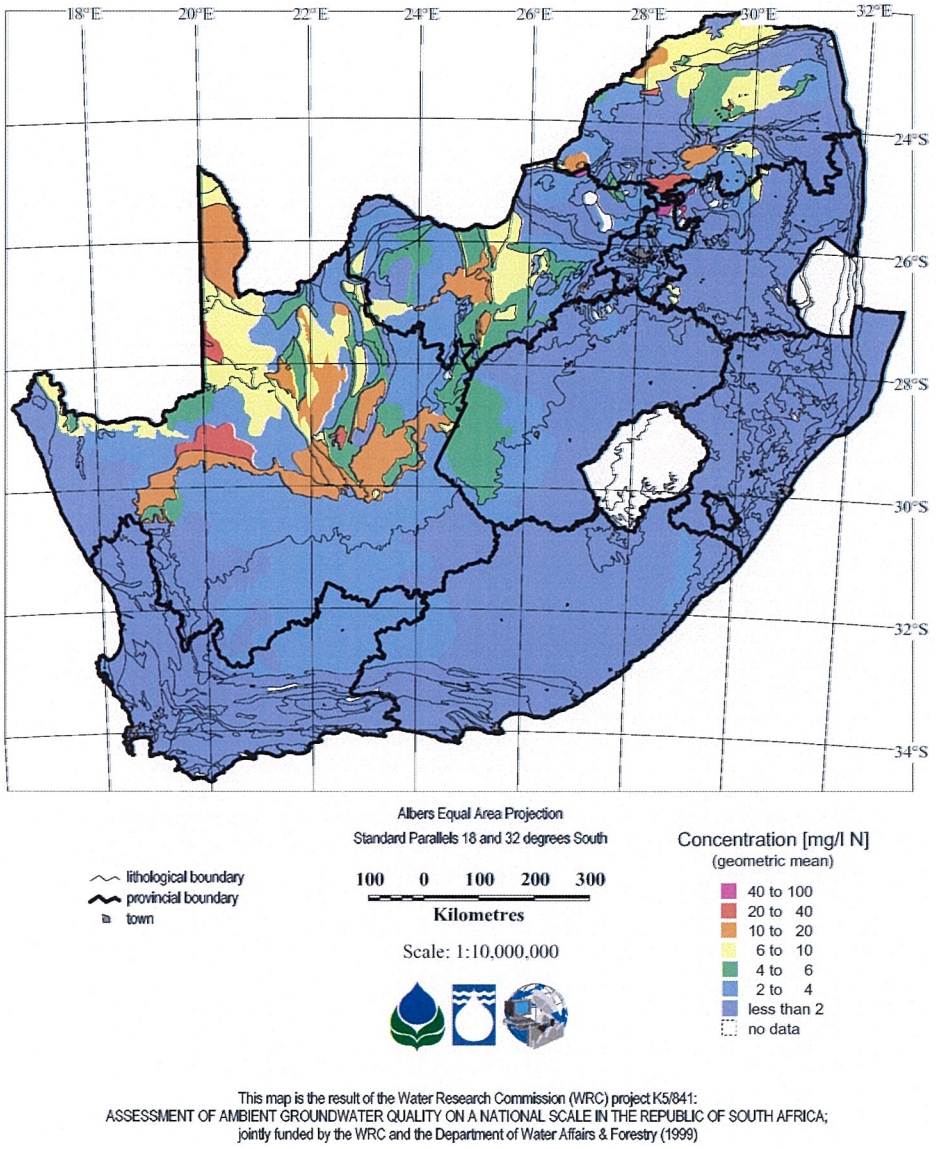


Figure 5: **National mapping of the concentration of Nitrogen in groundwater (reproduced from WRC, 2000)**

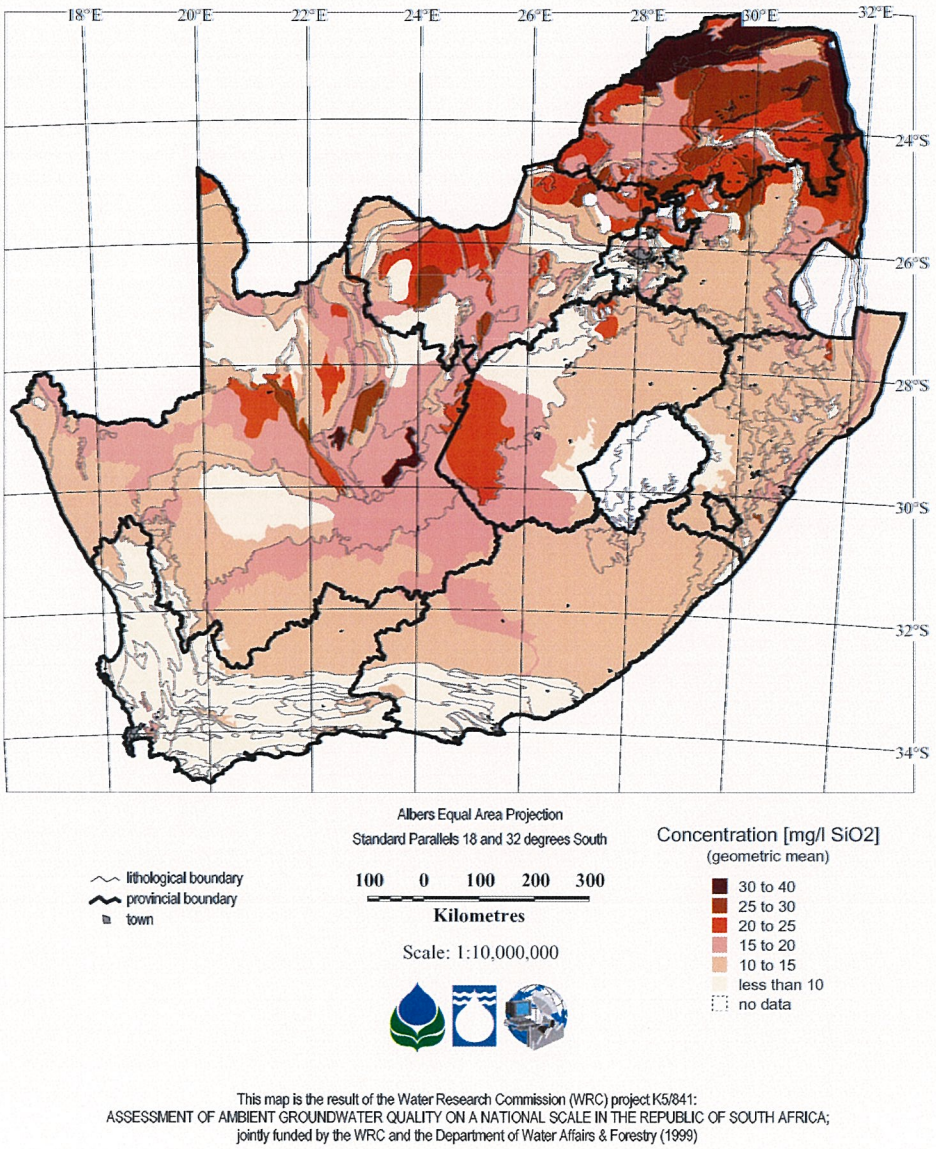


Figure 6: National mapping of the concentration of Silicates in groundwater (reproduced from WRC, 2000)

4.2 Physiography of Coastal Environment and Metocean Conditions

The major physical and chemical oceanographic features on the South African coastline of relevance to this study are as follows (Figure 7):

- North of Richards Bay where the Agulhas Current flows close inshore and strongly influences the nearshore and shelf conditions (*e.g.* Pearce, 1977; Gründlingh, 1983);
- Extending southwards from Richards Bay is a nutrient-rich upwelling zone inshore of the Agulhas Current (*e.g.* Lutjeharms *et al.*, 2000);
- The Natal Bight is a wide shelf region that is somewhat insulated from the Agulhas Current and is characterised by large to smaller scale eddies and re-circulations (Schumann, 1987, 1988a, 1988b) that together with the upwelling and enhanced phytoplankton levels in the northern extremity of the bight (Lutjeharms *et al.*, 2000) creates the necessary conditions for enhanced survivorship of early larvae and juvenile stages of pelagic spawners (Hutchings *et al.*, 2002);
- South of Durban the Agulhas Current again flow close inshore, its closest proximity to the coast occurring at Port Edwards (*e.g.* Gründlingh, 1983, Schumann, 1982, 1998). The Kwazulu-Natal coastline south of Durban comprises mainly sandy beaches with some rocky headlands, while further south, from just south of Port Edward to the Kei River, there exists a more rocky coastline with numerous small, sandy pocket beaches;
- Southwards of the Mbashe River mouth the Agulhas Current starts to diverge from the shelf edge, resulting in upwelling inshore of the Agulhas Current (*e.g.* Beckley and van Ballegooyen, 1992; Lutjeharms *et al.*, 2001);
- The shelf widens rapidly west of Port Alfred towards Port Elizabeth. This is a zone of major variability. Cold water eddies, intrusions of Agulhas water onto the shelf and large offshore meanders or excursions of the Agulhas Current all occur at this location (*e.g.* Boyd *et al.*, 1992; Goschen and Schumann, 1988);
- The ocean circulation over the Agulhas Bank, the wide shelf region extending from west of Port Elizabeth to Cape Point is strongly influenced by local and remote wind forcing and the adjacent Agulhas Current. The circulation over the shelf is complex with several gyre like patterns (Boyd *et al.*, 1992, Boyd and Shillington, 1994). Close inshore the currents run mostly from west to east while the bottom currents generally flow to the west. Strong upwelling occurs at capes under easterly wind conditions (*e.g.* Beckley, 1983). Retention mechanisms are likely to play a role in the larger embayments along this coastline (*e.g.* St Francis Bay, Algoa Bay);
- A strong shelf-edge jet occurs along the outer edge of the Agulhas Shelf, offshore of the Cape Peninsula and offshore of Cape Columbine (Armstrong *et al.*, 1987; Bang and Andrews, 1974; Boyd and Nelson, 1998; Nelson, 1985; Largier *et al.*, 1992; Shannon, 1985);

- Significant upwelling is observed from Cape Agulhas westwards. From Cape Point northwards substantial seasonal upwelling occurs, concentrated at a number of upwelling cells along the West Coast (*e.g.* Shannon, 1985, Nelson and Hutchings, 1983);
- The predominantly alongshore and offshore flows along the west coast are interrupted only by St Helena Bay that provides a re-circulation and retention zone (*e.g.* Penven *et al.*, 2000). Other nodal locations of interest are the Orange River mouth region and to a lesser extent the region around the Olifants River mouth;

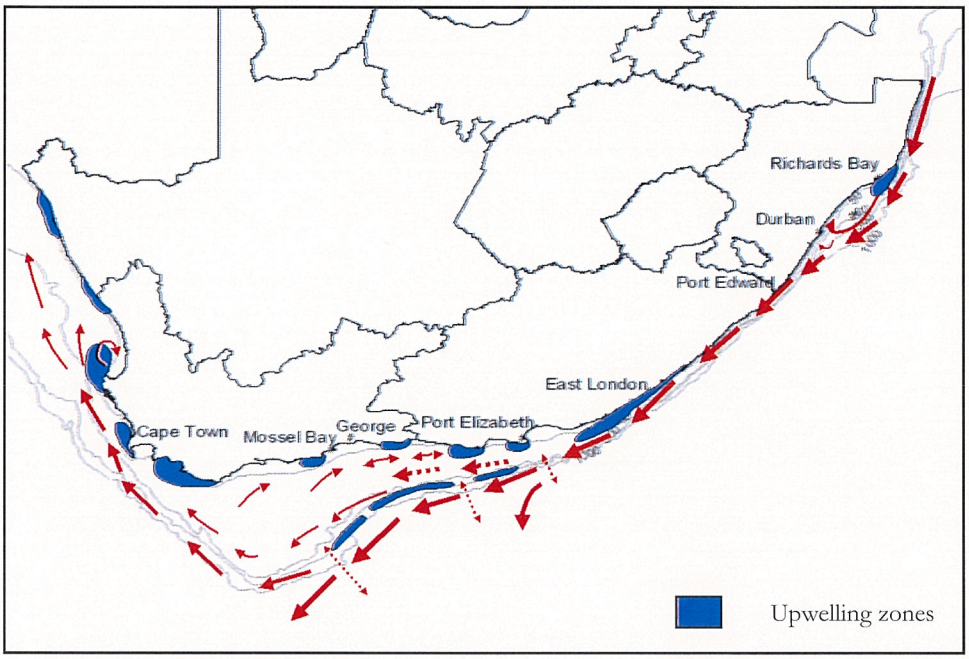


Figure 7: Schematic diagram of the major circulation features of the marine environment of southern Africa

Both the major physical and chemical oceanographic features along the South African coastline and the mechanisms determining spawning and recruitment success of marine fish suggest a more complex classification of biogeographic domains than the three biogeographic domains for typically adopted for the South African marine environment. However, to reduce the complexity of this preliminary initial assessment of the freshwater requirements of the South African marine environment, only three biogeographical domains are considered (Figure 8) in this study, namely:

- A cool-temperate region extending from the Orange River down the west coast and along the southwest coast to Cape Agulhas,
- A warm-temperate zone stretching from Cape Agulhas to approximately the Mbashe River mouth
- A subtropical region extending up the east coast from approximately the Mbashe River Mouth.

These biogeographic classification closely follow the estuary based classifications of Day (1981) and Whitfield (1994a).

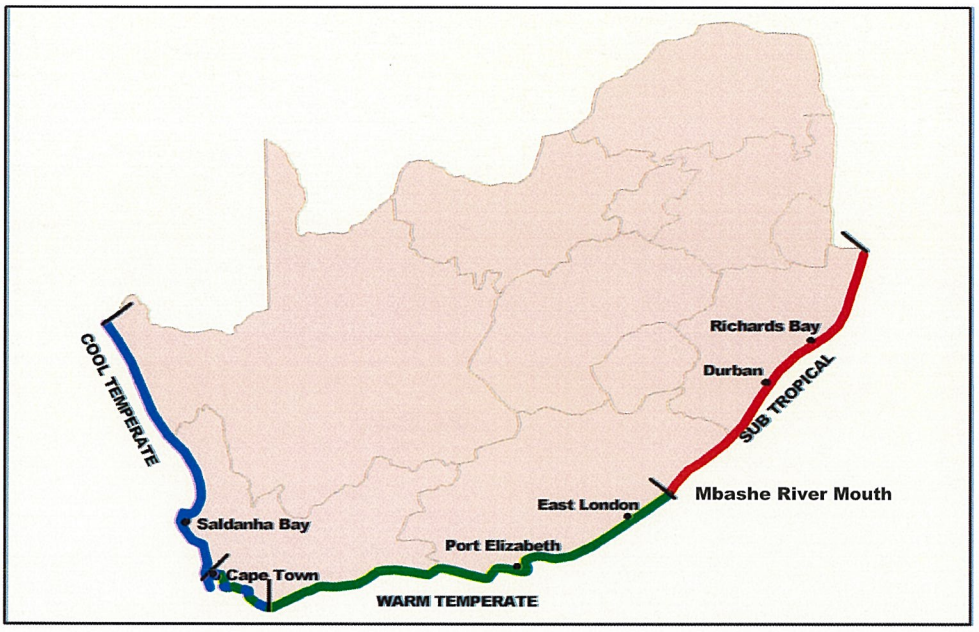


Figure 8: Biogeographical regions along the South African Coast as used in this study

Changes in the coastal morphology create sub-regions within these biogeographical domains as follows:

- The cool temperate region along the West Coast the coastline comprises predominantly long sand beaches, however north of the Olifants River the coastline is increasingly rocky. South of Cape Columbine is a number of rocky headlands with smaller sandy beaches. Similar coastal features occur east of Cape Point;
- The warm temperate zone stretching from Cape Agulhas eastwards to the Mbashe River Mouth comprises predominantly rocky headlands and associated large sandy embayments. Between Cape Agulhas and Mossel Bay the coastline is more rocky and comprises a number of smaller pocket beaches. North of the Kei River Mouth a similar rocky coastlines with smaller pocket beaches predominates;
- The subtropical region extending up the east coast from Mbashe northwards comprises a rocky coastline with small pocket beaches until Port Edwards where after the coastline comprises predominantly long sandy beaches interspersed by a few rocky outcrops and small headlands.

4.3 Distribution of Marine Biota

The biogeographical classifications of the South African estuarine, nearshore and offshore environments indicate a marked similarity for invertebrates (Emanuel *et al.*, 1992), rocky shore biota (Bustamante, 1994), intertidal fishes (Prochazka, 1994), shelf-associated fish species (Turpie, 2000), estuarine fishes (Day *et al*, 1981, Harrison, 2002), a general classification of estuarine systems (Day, 1981; Whitfield, 1992) and measures of biodiversity (Lombard and Strauss, 2004). These biogeographic classifications are summarized in Figure 9 and Table 4 below.

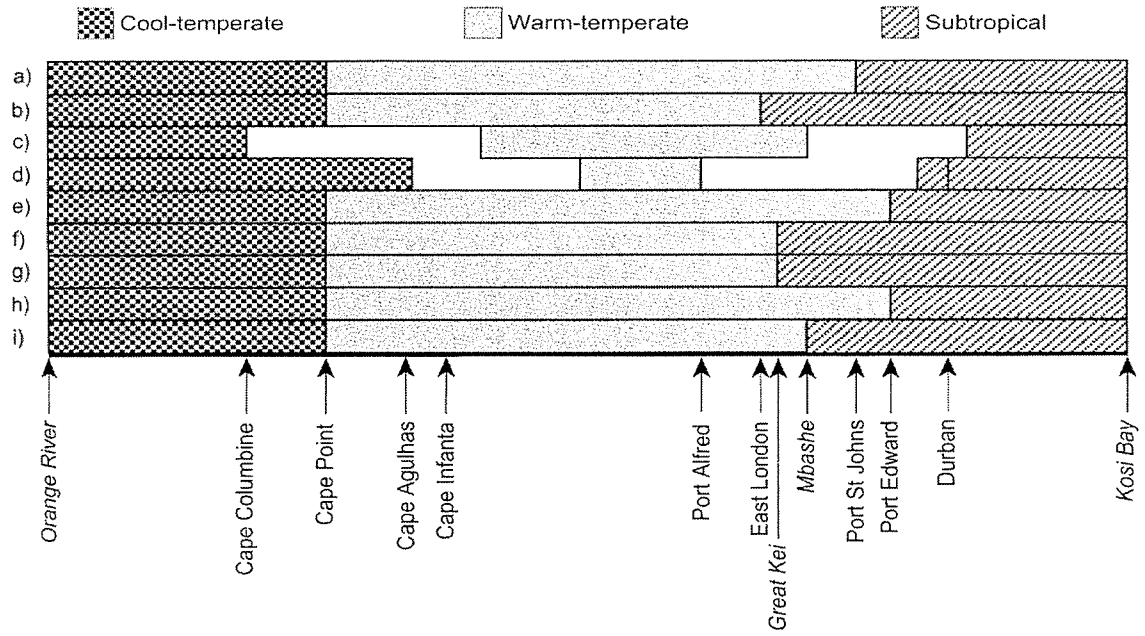


Figure 9: **Summary diagram indicating South African marine biogeographic provinces after: (a) Stephenson and Stephenson; (1972), (b) Emanuel et al. (1992); c) Bustamante (1994); (d) Prochazka (1994); (e) Turpie *et al.*, (2000); (f) Day (1981); (g) Day et al. (1981); (h) Potter et al. (1990); (i) Whitfield (1994). (after Harrison, 2002)**

Table 4: **Summary of biogeographic provinces of the marine environment of South Africa (adapted from Harris, 2002)**

ID *	Source	Basis of classification	Biogeographic provinces
a	Stephenson and Stephenson (1972)	Distribution of rocky shore biota	West Coast Province stretching down the West Coast to Cape Point
			Warm-temperate South Coast Province stretching from Cape Point to Port St Johns
			Subtropical East Coast Province stretching from approximately from Port St Johns to Mozambique

ID *	Source	Basis of classification	Biogeographic provinces
b	Emanuel *et al.* (1992)	Analyses of marine invertebrates	Cool-temperate Namaqua province from Lüderitz to Cape Point
			Warm temperate Agulhas Province from Cape Point eastwards to East London
			Subtropical Natal Province from East London north to Mozambique, comprising two provinces, one from Durban southward and the other from Durban Northward
c	Bustamante (1994)	Analyses of rocky shore biota	West-coast Namaqua province from Lüderitz to Cape Columbine
			South-coast Agulhas Province from Cape Infanta to the Mbashe estuary
			East-coast Natal Province from Ballito Bay (just North of Durban) to Inhaca Island, Mozambique
d	Prochazka (1994)	Analyses of Intertidal fishes	Namaqua Province, extending from Koppie Alleen, east of Cape Agulhas.
			Warm temperate Agulhas Province between Tsitsikamma and Port Alfred.
			Two east coast Natal Provinces, one from Pennington (just south of Durban) to Durban the other northward from Durban northward to Kosi Bay
e	Turpie *et al.* (2000)	Distribution and ordination of shelf-associated fish species	Cool-temperate region along the West Coast from the Orange River mouth to Cape Point
			Warm-temperate region from Cape Point to approximately Port Edward
			Sub-tropical region from Port Edward north to Kosi Bay.
f	Day (1981)	Estuarine classification based mainly on water temperature, rainfall and river flow	Cool-temperate estuaries between Orange River and Cape Point characterised by low rainfall and high evaporation
			Warm temperate estuaries between Cape Point and the Great Kei River characterised by minimum winter temperatures of between 12 and 14°C and variable rainfall
			Subtropical estuaries from the Great Kei River to southern Mozambique characterised by warm waters (>16°C) and good summer rainfall and discharge.
g	Day *et al.* (1981)	Faunistic provinces of estuarine fish	Cool-temperate province between Orange River and Cape Point
			Warm temperate province between Cape Point and the Great Kei River
			Subtropical province from the Great Kei River to southern Mozambique
h	Potter *et al.* (1990)	Analyses of marine biota (paper on analysis of role played by estuaries in the life cycles of fish)	Cold-temperate west coast region from beyond Walvis Bay to Cape Point
			Warm-temperate region from Cape Point to approximately Port Edward
			Subtropical east coast region from approximately Port Edward northwards to approximately 26°S
i	Whitfield (1994a)	Estuary –association classification of fishes	Cool-temperate region from the Orange River down the west coast to Cape Point
			Warm-temperate zone stretching from Cape Point to the Mbashe River
			Sub-tropical region extending northwards up the east coast from the Mbashe River
j	Harrison (2002)	Analyses of fish in South African estuaries	Cool-temperate region from the Orange River down the west coast and along the south-west coast to Cape Agulhas.
			Warm-temperate zone stretching from Cape Agulhas to just south of Port St Johns
			Sub-tropical region extending northwards up the east coast from Port St Johns.
k	Lombard and Strauss (2004)	large-scale biological variability and biogeography, plus large scale habitat differences related to different current systems with different temperatures and productivity	Namaqua bioregion extends from just north of the upwelling cell at Lüderitz to Cape Columbine;
			the South-western Cape bioregion extends from here to Cape Point
			the Agulhas bioregion extends from Cape Point to the Mbashe River
			the Natal bioregion extends from the Mbashe River to Cape Vidal
			the Delagoa bioregion extends from Cape Vidal northwards into Mozambique

* ID refers to the classification identity given in Figure 9.

4.4 Definition of Ecosystems (Biogeographical Domains)

As noted in earlier, both the major physical and chemical oceanographic features along the South African coastline and consideration of the mechanisms determining spawning and recruitment success of marine fish suggest a more complex classification of ecosystems in terms of biogeographic domains than the three biogeographic domains typically adopted for the South African marine environment. Consistent with this notion, initially five biogeographic domains were identified for the preliminary assessment, namely:

- Northern KwaZulu-Natal (including the Natal Bight);
- Southern KwaZulu-Natal and the Southeast Coast (north of the Kei River);
- The East Coast (stretching approximately from Port Elizabeth to the Great Kei River);
- The South Coast (stretching from Cape Agulhas to Port Elizabeth);
- And the West Coast (extending westwards from Cape Agulhas past Cape Point and up the West Coast to the Orange River).

The typical spatial scales of ecosystems and, consequently, the proposed scale of the assessments of marine ecosystems along the South African coastline are as follows:

- along the KwaZulu-Natal coast the waters are largely oligotrophic waters and the nutrient supply associated with the freshwater inflows are likely to be of greater importance. Similarly, the supply of sediments is reported to be of significance in meeting the habitat requirements of important fisheries species (*e.g.* prawns). The KwaZulu-Natal coastline between Durban and Richards Bay seemingly operates as one large ecosystem. Conditions north of St Lucia and south of Durban are somewhat different (*e.g.* limited sediment inputs to the marine environment). The freshwater inputs to the KwaZulu-Natal coast comprise inflows from many both small and larger estuaries. No one estuary, with perhaps the exception of the Thukela River, is likely on its own to have a substantial influence on the marine environment. The nutrient and sediment requirements of the marine environment in general can be achieved by many different combinations of inflow from estuaries in the region. This is particularly true of the Natal Bight region where there is significant retention of water both in the nearshore and shelf regions, while sediments here have a longer residence time than would be expected for other more exposed shelf environments.. However, it may be that single estuaries whilst having only a limited role in terms in terms of supplying nutrients and sediments to the marine environment, may play a critical role in terms of their nursery function due to the limited number of estuaries having a major nursery function in this region. The above characteristics suggest that a ***regional assessment would be most appropriate in this region***. Although there are a number of estuaries supplying freshwater, nutrients and sediments to the coastal region south of Durban, on such a coast that is under greater influence of the Agulhas Current, these inputs are unlikely to create a continuous habitat

(*i.e.* similar to that of the Natal Bight) anywhere but in the very nearshore and surf zone. Here the role of individual estuaries at any particular location along the coast is expected to be greater and a regional assessment would seem to be of less relevance.

- The Eastern Cape Coast, extending from the Kei River to just of Port Edward comprises a more rocky coastline with numerous small, sandy pocket beaches and many small estuaries. This coast is also swept by the Agulhas Current that typically lies close inshore. In terms of ecological functioning and habitats, the influence of individual estuaries is likely to be of limited spatial extent. A ***more nodal assessment thus seems appropriate.*** The implication of this is that an assessment of freshwater reduction in an individual estuary and its impact on the marine environment may be of greater relevance here than would be the case in the Natal Bight. However the existence of many estuaries along this coastline would suggest that the role of individual estuaries may be more limited than suggested above.
- Along the South Coast, from Cape Point to Algoa Bay, the coastline comprises a number of large bays separated by sweeping beaches and prominent headlands. The Agulhas Current lies far offshore while the flows over the adjacent shelf are largely wind-driven despite the strong influence of the Agulhas Current. Here the ecosystems functions largely on a coastal embayment scale, however the ecosystems further offshore are more spatially extensive. The influence of freshwater flows are likely to be limited in this offshore zone, except for perhaps sediment inputs. This suggests that assessment of the freshwater requirements of the marine environment should ***focus mostly on the scale of the large coastal embayments.***
- On the West Coast, the more limited number of rivers and estuaries and their relative remoteness from one another suggest that ***a nodal assessment approach is required.*** Along this coastline it would seem reasonable to assess the contributions of the various estuaries individually as the influence of an individual estuary is unlikely to be of sufficient spatial extent to overlap with that of an adjacent estuary. In upwelling regions (West Coast), where dissolved nutrients are generally in adequate supply, other issues such as the role of freshwater plume dynamics in creating a favourable environment for increased water column productivity (*e.g.* in increasing water column stability), and sediment and particulate organic matter discharges into the nearshore environment are likely to be of greater importance.

The groundwater flows to the marine environment indicate broadly similar assessment requirements as those indicated above, *i.e.* predominantly discrete discharges on the west and southwest coasts and diffuse groundwater discharges along the East Coast.

The ecosystem functioning in the various biogeographical domains being assessed is thus sufficiently different to require region-specific assessments. An additional complexity is that the various domains on moving offshore (estuarine, nearshore/surf-zone and shelf) are often quite distinct in terms of their ecological functioning.

Despite the differences described above, as noted previously, to reduce the complexity of these initial assessments only the three broader biogeographical domains typically considered in most assessments of the South African coastline (Figure 8) are utilised here, namely: ,

- A cool-temperate region extending from the Orange River down the west coast and along the southwest coast to Cape Agulhas,
- A warm-temperate zone stretching from Cape Agulhas to approximately the Mbashe River mouth
- A subtropical region extending up the east coast from approximately the Mbashe River Mouth.

5. Resource Utilization

As discussed in Part I: Section 4.3 of this report, resource utilization can be categorized according to utilization in terms of:

- Ecological Services
- Living Marine Resources
- Recreation and tourism
- Industrial.

The effect of changes in freshwater inflows to the marine environment, while expected to be of limited consequence for industrial uses of the marine environment, may impact upon recreation and tourism. For example, changes in sediment fluxes associated with freshwater inflows may be of significance in terms of changes in shoreline stability and its effects of coastal infrastructure. However, by far the greatest effect of changes in freshwater flow on ecosystem services supported by marine ecosystems is expected for ecosystem health and functioning and living marine resources, both of which support recreational and tourism activities in the coastal zone. For this reason the focus here on the first two bullets above, namely ecological services and living marine resources.

5.1 Ecological Services

5.1.1 Spawning and nursery areas

The South African coastline, being one of the smoothest and least convoluted (*i.e.* with the lowest fractal index) in the world and being swept by strong currents, has relatively few habitats suitable as spawning and nursery areas. Hutchings *et al.* (2002) identify four important southern African spawning grounds (mainly fish), three of which are relevant to this study, namely the ***Natal Bight nursery ground***, the ***Agulhas Bank nursery ground*** and the ***inshore West Cape coast*** (Figures 10 to 12). A broad overview of the role of the various regions in maintaining

viable fisheries of socio-economic importance and the maintenance of biodiversity is provided here, highlighting the spawning grounds and associated enrichment, retention and concentration mechanisms of relevance.

Many of the dominant fish species, and even squid, move upstream to spawn, the spawning typically occurring downstream of productive upwelling zones. This is the case in each of the above regions. Other species spawn close inshore and probably rely on re-circulation within embayments and limited alongshore displacements to maintain discrete stocks (Hutchings *et al.*, 2002). The role of estuarine and calm inshore regions as nursery areas is discussed in Part I: Section 4.5.3 of this report.

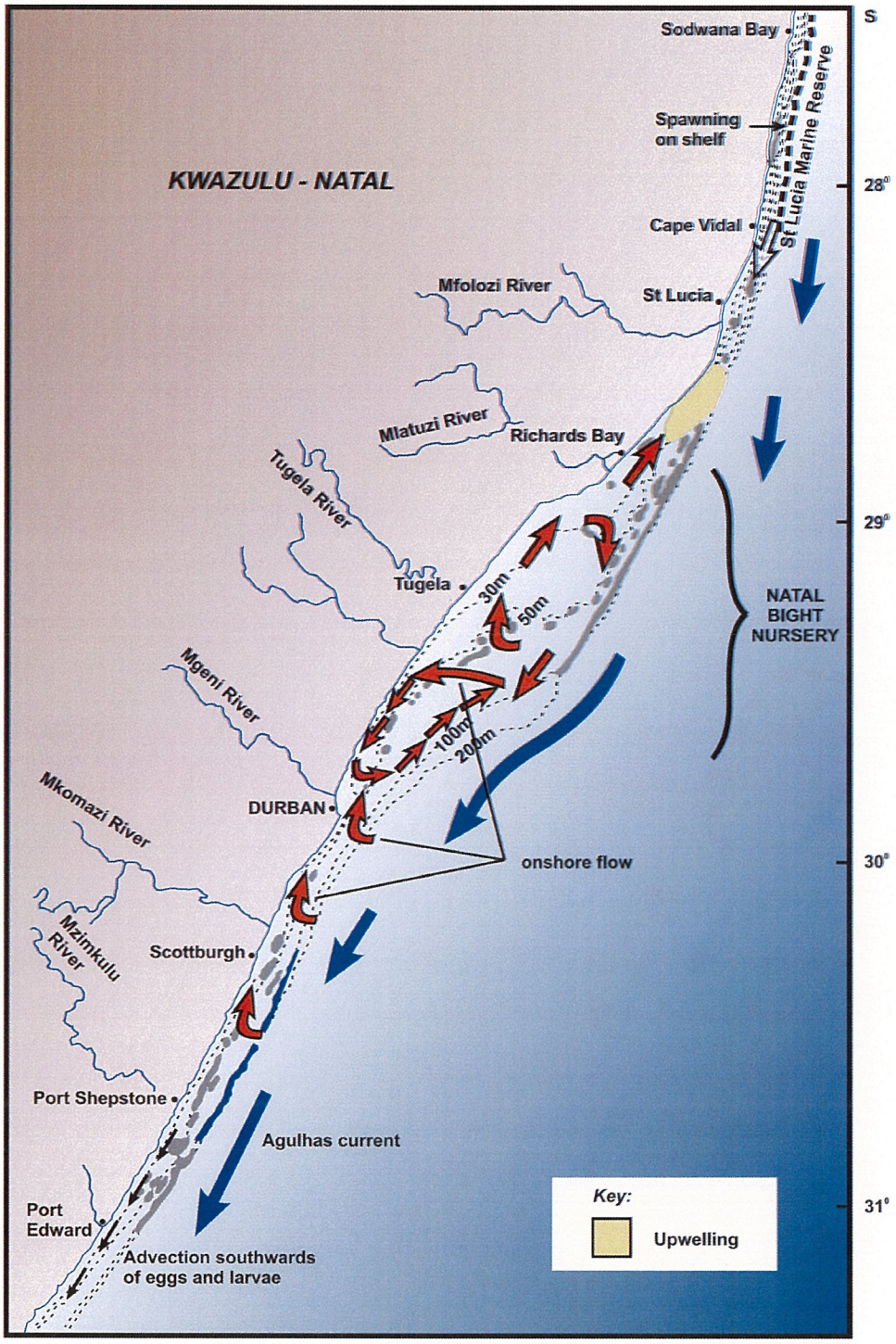


Figure 10: The Natal Bight nursery area, showing the major circulation features, the distribution of reefs, major rivers and bottom topography (adapted from Hutchings *et al.*, 2002)

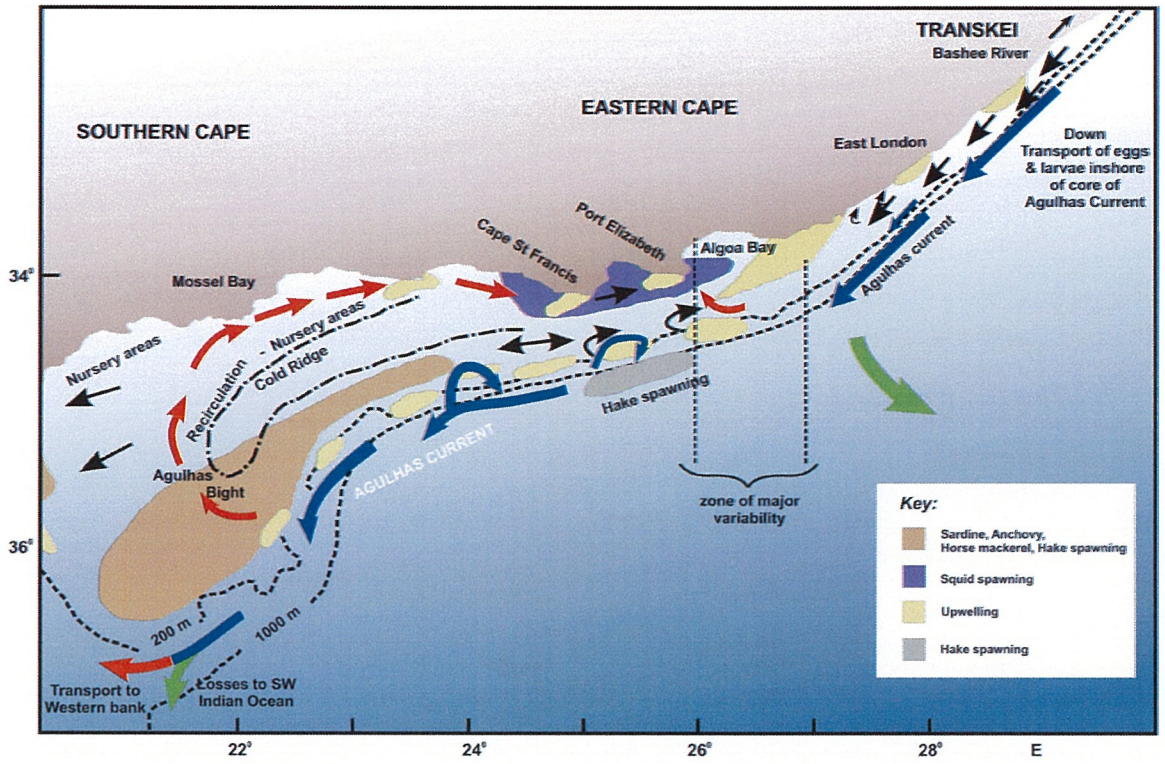


Figure 11: The Agulhas Bank nursery area, showing the major circulation features, the major embayments and bottom topography (adapted from Hutchings *et al.*, 2002)

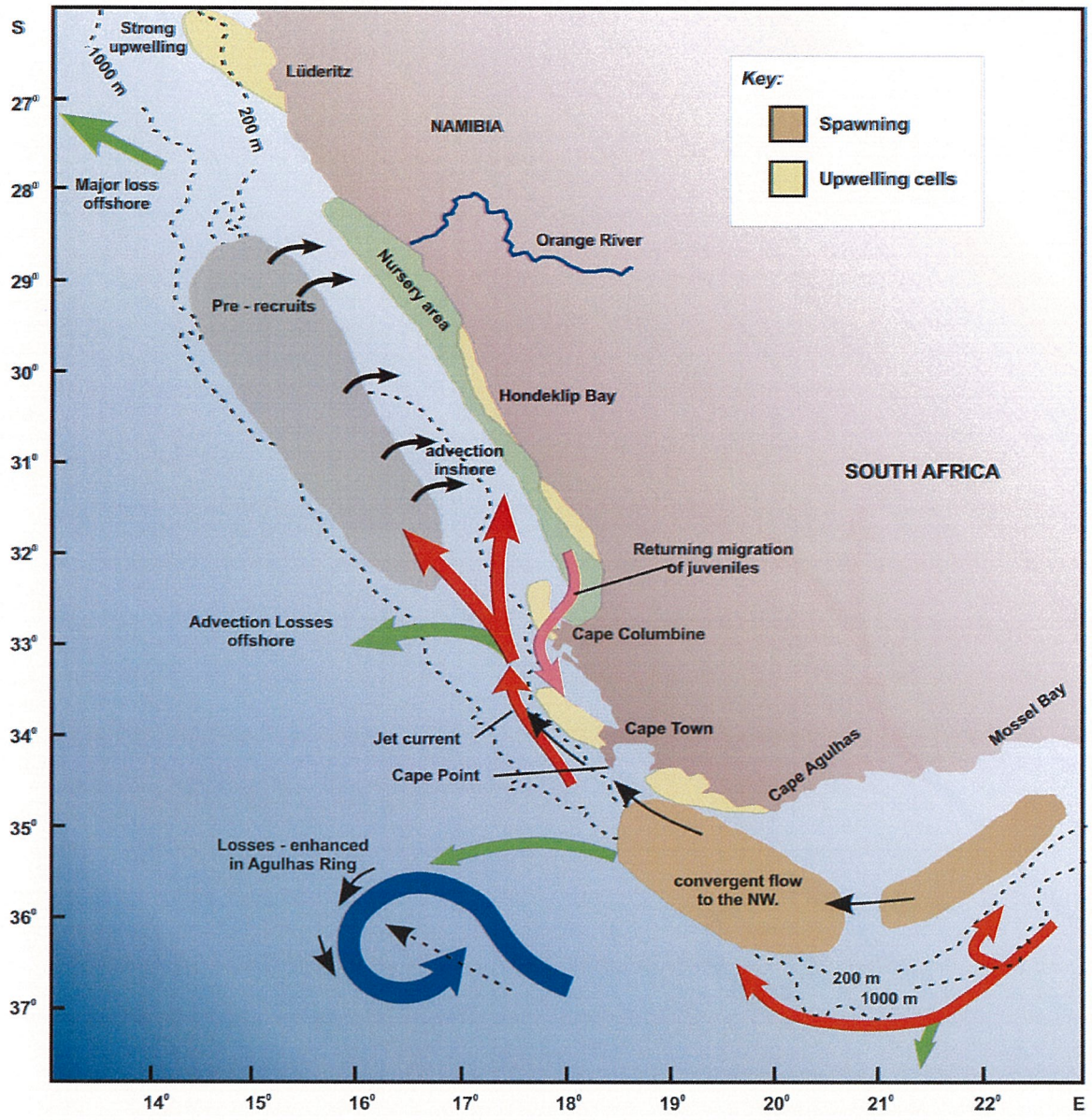


Figure 12: **The inshore West Coast nursery area, showing the major circulation features and bottom topography (adapted from Hutchings *et al.*, 2002)**

5.1.2 Marine protected areas

A rough mapping of existing and proposed Marine Protected Areas and marine and terrestrial conservations areas is contained in Figures 13. Figure 14 comprises a map of declared Marine Protected areas reproduced from Lombard and Strauss (2004) that also provide a more comprehensive description of the bio-zones of the South African marine environment.

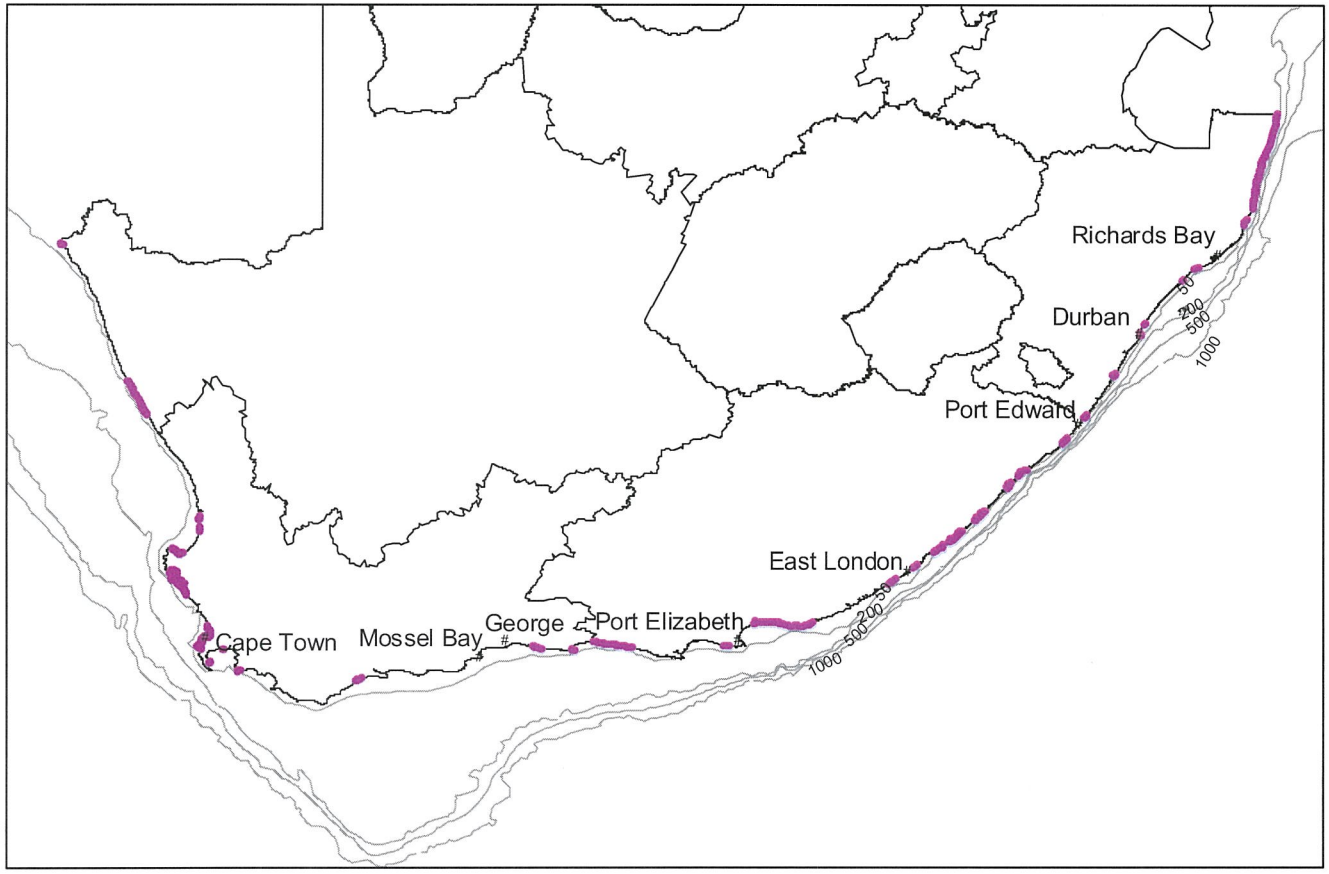


Figure 13: Existing and future Marine Protected Areas and marine/terrestrial conservation areas

[This figure was produced using information from the following publications: Atwood *et al.* (1997), Jackson and Lipschitz (1984), Robinson and de Graaff (1984), Whitfield (2000) and Lombard and Strauss (2004). The names and locations of ecologically sensitive and marine protected areas are listed in Table 5.]

Table 5: The ecologically sensitive and marine protected areas mapped in Figure 13

	MARINE RESERVES	GENERAL RESTRICTED AREAS	SINGLE SPECIES RESTRICTED AREAS	NATIONAL PARKS	PROVINCIAL ORDINANCE	OTHER
Northern Cape	Namaqualand Marine Protected Area		MacDougall's Bay	Spoeg – Groen National Park (Namaqualand Coast)		Orange River Mouth (Ramsar site)
Western Cape	Rocher Pan Millers Point HF Verwoerd De Hoop Goukamma Robberg Cape Peninsula MPA	Scarborough to Hoek van Bobbejaan Jagger's Walk to Glencairn Kalk Bay to St James Muizenberg to St James Strand Mudge Point Haarderbaai Walker Bay	Stompneus Bay rock lobster sanctuary Saldanha Bay rock lobster sanctuary Table Bay rock lobster sanctuary Melkbos/Die Josie rock lobster sanctuary Dyer Island abalone sanctuary Kommetjie rock lobster sanctuary	West Coast National Park Table Mountain National Park Wilderness National Park Knysna National Lake Area	Rocher Pan Nature Reserve Diep Estuary Krom Estuary Heiningnes Estuary Goukamma Estuary Keurbooms Estuary Robberg Nature reserve	Verlorenvlei Ramsar Site Langebaan Lagoon Ramsar site Swartklip / Wolfgat Sanctuary World Heritage Site: Cape Floral Kingdom
Eastern Cape	Sardinia Bay Dwesa-Cwebe Hluleka Mkambati Pondoland MPA Bird Island MPA	Nahoon Point to Ganubie Point Christmas Rock to Gxulu Mouth Nyara Mouth to Kei Mouth		Tsitsikamma National Park Greater Addo National Park (proposed)	St Croix Island Seekoei Estuary Gamtoos Estuary Quko Estuary Manubi Marine Nature Reserve Mbashee Estaury Hluleka Estuary Msikaba and Mtentu Estuaries Ndluzula Nature Reserve Mgazana Nature Reserve Silaka Nature Reserve Mkambati Nature Reserv e	
KwaZulu-Natal	Trafalgar St Lucia Maputaland Aliwal Shoal MPA				Mpenjati Estuary Mdoni Park Beachwood Creek Mhlanga lagoon Nyoni Estuary Mlalazi/Siyai Estuary Richards Bay Mfolozi Estuary St Lucia Estuary Mgobezeleni Estuary Kosi Bay Estuary	World Heritage Site: Greater St Lucia Wetland Park.

These data have been compiled from the following sources: Atwood *et al.* (1997), Jackson and Lipschitz (1984), Robinson and de Graaff (1984), Whitfield (2000) and Lombard and Strauss (2004).

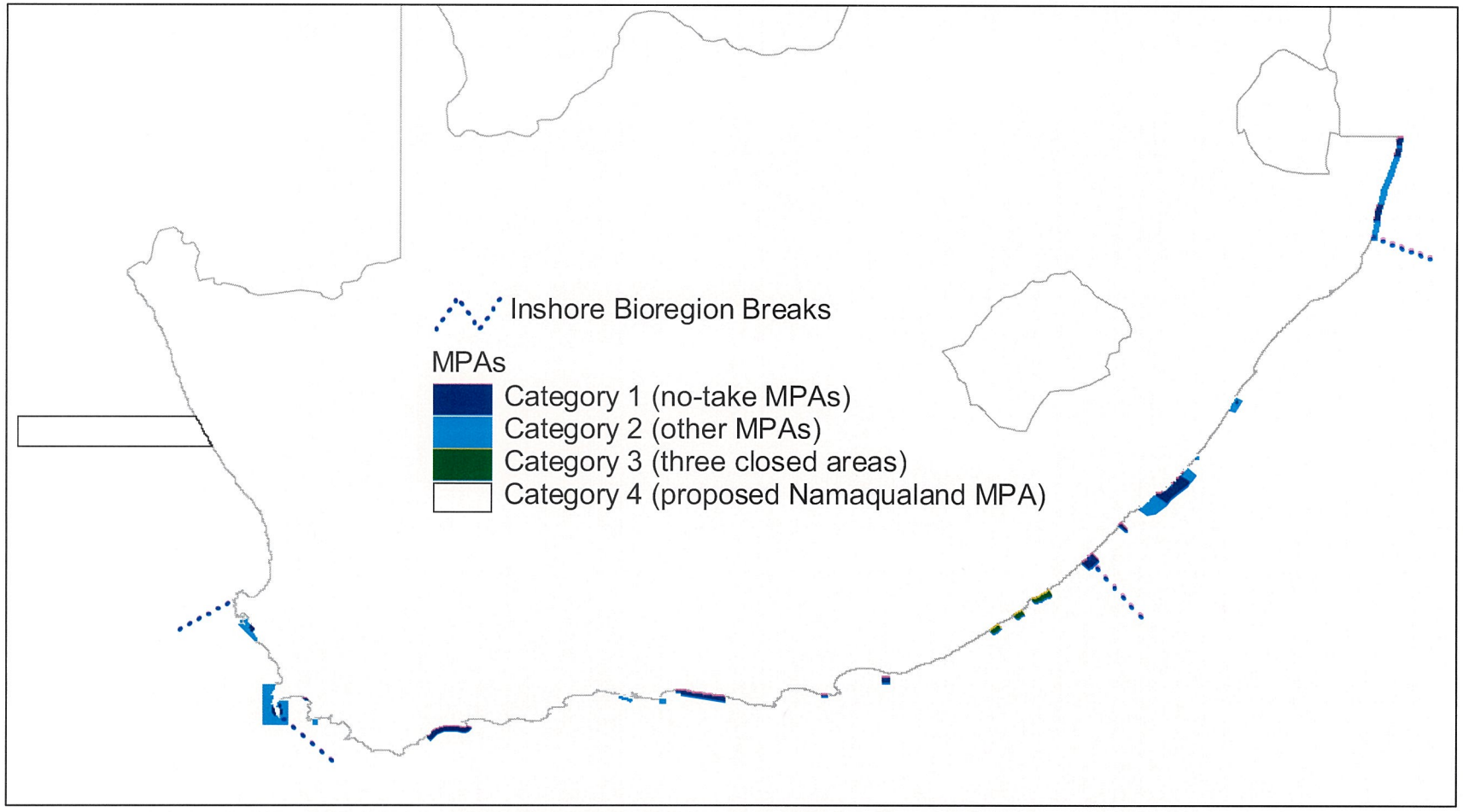


Figure 14: Declared marine protected areas (reproduced from Lombard and Strauss, 2004).
source: http://bgis.sanbi.org/NSBA/marine.asp#otherdata

5.2 Exploitation of Living Marine Resources

5.2.1 Subtropical region

The subtropical region extends up the east coast from approximately the Mbashe River Mouth to the northern border of South Africa.

The shores of KwaZulu-Natal are intensively used by people who mainly access its marine resources, probably to a greater degree than elsewhere on the South African coastline. The north-eastern Eastern Cape (formerly Transkei) coastline is also relatively well-utilised in terms of its marine resources. The use of natural resources in these regions involves a variety of activities both in the intertidal zone and offshore, including recreational, commercial, subsistence and tourism-related activities that are centred around estuaries, rocky and sandy shores and the waters over the continental shelf, especially the coral and rocky reefs.

The fisheries in this region include commercial, recreational and subsistence fisheries. The commercial sector in this region is modest in the number of participants, but has a considerable local economic value along the KwaZulu-Natal coastline. Along the Kwazulu-Natal coastline the commercial fishing activities (*e.g.* MCM, 2002, Fennessy *et al.*, 2000) include:

- oyster gatherers that operate on rocky shores south of the Thukela River;
- harvesters of estuarine prawns that operate drag nets in Richards Bay harbour, harvesting swimming prawns and schooling fishes for bait;
- marine seine netters that are mostly active along the South Coast during the seasonal sardine run;
- the prawn trawlers that target shallow water prawns in shallow waters of the Tugela Bank offshore of the Thukela River and on the St Lucia Banks, and harvest a mixed catch of prawns, langoustine, crabs and rock lobsters in deeper waters along the continental shelf north of Durban. The bycatch roughly includes fish (23 tonnes), crab (10 tonnes) and cephalopods (4.5 tonnes);
- a significant commercial line fishery totalling approximately 765 tonnes per annum with an economic value (including contributions by subsidiary industries) of approximately R 29 million (Louw, 2003);
- the recreational line fishery comprises an annual catch of approximately 470 tonnes per annum with an economic value (including contributions by subsidiary industries) of approximately R 45 million;

The recreational and commercial line fisheries differ in that recreational fishers tend to target pelagic gamefish species whereas commercial fishers target the more highly valued reef and shoaling species. The recreation catch comprises mostly king mackerel and yellowfin tuna, while slinger and geelbek are the most important commercial species (Lamberth, 2003).

Other recreational activities include:

- cast-netting primarily for baitfish;
- recreational spear-fishing;
- recreational diving on reefs (either from shore or boats);
- recreational invertebrate harvesting.

Artisanal and subsistence fisheries in this region include linefishing, gill-netting, traditional fish traps (Kosi Bay) and invertebrate harvesting (mussels, red bait, rock lobsters, ghost crabs, *etc.*).

Along the north-eastern Eastern Cape coastline commercial fishing activities primarily comprise a limited commercial line fishery of typically less than 30 tonnes per annum (MCM, 2002). However subsistence recreational invertebrate harvesting and fishing activities are expected to be significant. Recreational activities include:

- recreational spear-fishing;
- recreational diving on reefs (either from shore or boats);
- recreational invertebrate harvesting.

Tourist activities occur along the whole coast in the subtropical region and include sun-bathing, swimming, surfing, sailing, diving, *etc.* Associated with these activities is significant infrastructure, particularly along the KwaZulu-Natal coastline. Of importance in this regard is the preservation of ecosystems in support of ecotourism, the avoidance of long-term erosion of coastal developments and alteration of recreational beaches in a manner that eventually detracts from their recreational potential.

5.2.2 Warm temperate region

Along the Cape South Coast coastline and the coastline extending north-eastwards to the Mbashe River mouth, the commercial fishing activities are as follows (*e.g.* Japp *et al.*, 1994, MCM, 2002):

- a demersal inshore trawl fishery that include hake, horse mackerel, panga, Agulhas sole, kingklip, Cape gurnard, silver kob and chokka squid (Booth and Hecht, 1998; Japp *et al.*, 1994, MCM, 2002);
- chokka squid fishery (jigging) and catches of chokka, red squid, octopus as a bycatch of the trawl fishery;
- the South Coast rock lobster fishery;
- a substantial commercial line fishery of considerable diversity (MCM, 2002), with the most important species, in terms of potential impacts by changes in freshwater inflows to the marine environment, likely to be those with a strong estuarine or inshore dependency in their life cycle (*e.g.* Lamberth and Turpie, 2003). A large number of fish species make up the line fishery, mostly reef dwelling species, however the largest portion of the catch

is attributed to only a few species, in particular kob, geelbek and yellowtail (Japp *et al.*, 1994);

- beach-seine fisheries land approximately 120 tonnes of mullet with approximately 10% additional catch of other fish species (MCM, 2002);
- seaweed harvesting along the East Cape (and former Transkei) coastline;
- harvesting of wild oysters in the intertidal area mainly along the South Coast by oyster pickers;
- artisanal and subsistence fisheries that include linefishing and invertebrate harvesting (mussels, red bait, rock lobsters, *etc.*);
- recreational fisheries that include:
    - the recreational line fisheries of this region;
    - cast-netting primarily for baitfish;
    - recreational spear-fishing and diving on reefs (either from shore or boats);
    - recreational invertebrate harvesting.

5.2.3 Cool temperate region

The cool temperate region extending westwards from Cape Agulhas (or Cape Point depending on the basis of the definition) and up the West Coast to the Orange River, is highly productive with a high degree of commercial exploitation of these resources (*e.g.* Crawford *et al.*, 1987, MCM, 2002). However most of these resources are likely to display little or no dependency on the freshwater inflows (and associated changes in abiotic and biotic drivers), certainly not to the same extent as in the other biogeographical domains of southern Africa. However, there may be a significant impact directly or indirectly on the inshore living marine resources, particularly in the vicinity of estuary mouths along this coastline. Potentially the most important resource exploitation in this regard includes:

- a substantial inshore line fishery;
- the beach-seine and gillnet fisheries with a reported catch approximately 1 000 tonnes (predominantly harders *Liza richardsonii*) in this regions and an approximately 10% additional catch of other fish species (MCM, 2002). Due to gross under-reporting, it is estimated that this fishery is significantly larger (MCM, 2002) than generally reported.

The exploitation of living marine resources in all of the regions considered includes both consumptive and non-consumptive use. In terms of consumptive use the fisheries of importance are commercial fisheries, artisanal and subsistence fisheries and recreational fisheries, each having its own unique socio-economic dynamic (see Part I: Section 4.7) and consequent importance as an exploitable resource. Due to their being both coastal and of a local nature and the limited flexibility and resilience of participants, the artisanal and subsistence fisheries are expected to be particularly strongly impacted upon by changes in the resource availability and ease of

exploitation[33]. The economic consequences for commercial fisheries of changes in the resource availability and ease of exploitation also are likely to be significant. However recreational fisheries and other recreational activities associated with living marine resources are somewhat "buffered" from such direct socio-economic consequences (*e.g.* a decrease in catch per unit effort in a recreational line fishery is unlikely to deter recreational line fishermen from their activities, provided such changes are not extreme). Consequently the impact on the regional economy may be somewhat more limited than expected.

Given that the marine environment and estuaries are strongly linked in terms of their ecological functioning, *e.g.* there are a number of marine species that have an estuarine phase in their life cycle and *vice versa*, a deteriorating marine environment adjacent to estuaries (due to changes in freshwater inputs to these environments) is likely to result in less healthy estuarine environments. For this reason, the exploitable fisheries of estuaries should also potentially be considered here.

6. Approach to Scientific Assessment

6.1 Keystone and/or Indicator Species

The broad scope of the initial assessment and the lack of specific agreed upon management objectives and environmental quality objectives made it difficult to *a priori* select specific keystone or indicator species. The approach taken thus has been to identify ecological response categories, *i.e.* broad classifications of marine biota that are expected to respond to the largely abiotic drivers listed in Section 6.2 below (and discussed in greater detail in Part I: Section 4.5.3 of Part I). The broad categories utilised in the assessment are as follows:

- phytoplankton;
- benthic algae (micro and macro);
- holo-zooplankton;
- benthic Invertebrates (including larval stage, *i.e.* mero-zooplankton);
- fish;
- birds;
- mammals;
- reptiles (turtles), and;
- a non-ecological response category, comprising shoreline and beach erosion (that includes development, tourism and recreational issues not related to the direct utilisation/exploitation of living marine resources)

33 Viewing traditional fisheries in the same economic terms as other fisheries is misleading in terms of their importance, in that these fisheries form an integral part of the survival of communities that rely on them for a protein source.

At the initial workshop the specialists expressed concern at these categories as it was felt that they were too broad to be meaningful in all cases. This concern is justified as, on occasion, the behaviour or response within the various categories proved to be inconsistent, *i.e.* the response of various species within the same broad group/classification to a specific driver is significantly different. This highlighted the need to identify keystone or indicator species of relevance in the various biogeographic domains before proceeding with a more detailed assessment of ecological responses to changes in freshwater inflows to the marine environment.

Given that the identification of keystone species typically requires the specification of clear management objectives and associated environmental quality objectives (not undertaken here), and that this initial assessment is intended only to provide a broad overview of the freshwater requirements of the marine environments of South Africa, it was decided to acknowledge this deficiency but nevertheless to proceed with the broad classifications proposed above. This "bottom-up" approach has been supplement with a "top-down" approach based on evaluations of the life cycles of keystone and/or indicator species and their associated habitat requirements in terms of factors influenced by changes in freshwater inflows to the marine environment. This "top-down" approach has been followed wherever there is adequate data and/or a sufficient knowledge of the biotic response of an indicator species with respect to changes in freshwater inflows to the marine environment.

Since no specific keystone species were identified for the initial assessment, the generic life cycle and habitat requirements of each of the ecological response categories needed to be considered and related to the drivers identified as being relevant in the various biogeographical domains. This was attempted (albeit rather unsuccessfully) at the initial two day workshop.

Ideally, the assessment should focus on habitat requirements of species that are sensitive indicators of changes in ecosystem functioning due to a reduction of freshwater inflows to the marine environment (*i.e.* sensitive to changes affecting the environmental quality objectives of relevance to the region). Further, only the most critical life stages should be focussed upon.

In terms of the habitat requirements of keystone or indicator species, the focus should be on:

- recruitment success, *i.e.* survival particularly during the early stages of life (*e.g.* of prawns and fish), translating into the "strength" or size of a cohort;
- productivity (*e.g.* food availability during major growth stages and leading to spawning success)

In addition, should a fishery be based on the keystone or indicator species being assessed, then the role of freshwater flow (or the lack thereof) and its effect on catchability also need to be considered as this may bias the data (*e.g.* CPUE) used to assess recruitment success and productivity.

6.2 Relevant Habitat Components (Drivers)

The main drivers considered to be of relevance in assessing the potential impacts of the reduction of freshwater inflows (including both surface runoff and submarine groundwater discharges) to the marine environment of South Africa (summarised in Part I: Section 4.5.3), are as follows:

- *Availability of estuaries as nursery areas for marine biota with an estuarine dependency (i.e. an estuarine nursery function):* The availability of an estuarine nursery function is determined by both estuarine habitat suitability or health and the estuarine mouth condition;
- *Cueing effects;*
- *Availability of physical habitat as defined by the distribution of marine sediments:* Here both the quantity and quality (*i.e.* grain size distribution and organic content) of mainly inorganic sediment loads into the marine environment *and* their deposition in coastal and offshore environments to provide an appropriate physical habitat, are considered;
- *Fronts and other retention mechanisms*: This includes both water column stratification that ensures that phytoplankton remains in favourable light conditions and the accumulations of phytoplankton, zooplankton and other marine biota at both horizontal and vertical fronts;
- *Nutrient availability in the marine environment:* For the purposes of this assessment we have divided the nutrient inputs into the marine environment as dissolved nutrients and particulate organic matter (POM);
- *Physico-chemical variables, including temperature, salinity and turbidity.*

Based on the broad ecological categories (the equivalent of "keystone or indicator species" in this assessment) and the specialist knowledge of their habitat requirements, an analysis of the ecological response of the various ecological categories to the various identified drivers has been undertaken. In this manner hypotheses have been developed for the South African marine environment that attempt to describe potentially freshwater dependent processes (drivers) and associated ecological responses. Some hypotheses are generally accepted, others are more speculative.

The specialist attending the initial workshop were asked to specify the exact nature of the data and information that would be required to confirm and quantify ecological responses to changes in the drivers considered to have a freshwater dependency. The specialists were requested not to constrain their thinking according to known data availability and/or measurement constraints but rather to provide idealised data/information requirements for the proposed assessments. This allowed subsequent freedom to choice of the source of data and/or measurement/modelling techniques to be used to characterise the driver (*i.e.* the driver could be measured directly and/or derived using other data or model simulations).

One of the likely major constraints of any assessment such as those proposed here, is the availability of appropriate data. For example, a driver-response method where the ecological

response is assessed at the "first interface" between abiotic drivers and the ecological response, is likely to be constrained due to the lack of data to assess ecological responses (*e.g.* the response of phytoplankton to nutrient input to the marine environment requires phytoplankton abundance/production data that is unlikely to be readily available).

6.3 Functional Relationships

Part I: Section 4.5.4 details some of the functional relationships that may be used to characterise the abiotic drivers. A strong functional relationship exists between the drivers and:

- changes in freshwater inflows to the estuary;
- the estuary mouth condition;
- the metocean conditions prevailing in the adjacent marine environment, and;
- in the case of submarine groundwater discharges, the magnitude of submarine groundwater discharges and the nutrient concentrations in the groundwater at the point of discharge.

The workshop participants were asked to define the temporal and spatial scales of relevance in characterising the drivers. These are:

- the temporal and spatial scales at which the biota responds to the various drivers;
- the temporal and spatial scales that need to be resolved in order to adequately characterise the drivers;
- the duration and spatial extent of the data record required to adequately characterise the drivers and to quantify the relationships between driver(s) and the biotic response.

The metocean conditions in the marine environment that play a major role in determining the exact nature of the drivers, were also considered in terms of determining the characteristics scales of potential drivers.

6.4 Information Requirements

Based on the requirements to characterise the drivers in an appropriate manner, a gap analysis was undertaken to determine what data was still required and what measurement/modelling techniques could be used to provide these data. Such a gap analysis requires:

- that the availability of the relevant data be assessed, and
- that additional data requirements be identified
- those requirements for additional data collation/collection, modelling activities and research studies, be assessed.

From the gap analysis flowed suggestions for data collation activities, measurement programs, proposed modelling studies and research studies. The most important measurements required were identified as:

- **Estuarine health** and **estuarine mouth conditions,** both of which determine the extent to which estuaries are able to fulfil their nursery function (*i.e.* in terms of providing safe habitats or through the provision of cues for recruitment):

  Estuarine health, in terms of being able to act as a suitable nursery area, is dependent on a host of factors. Possibly the most important of theses is the presence of suitable habitat-forming species (*e.g.* mangroves, seagrasses). Also import is the hydrodynamic and water quality conditions within a particular estuary.

  It may be that in a region only a handful of estuaries provide a significant nursery function for the species under consideration. For example, in KwaZulu-Natal only three systems are considered to provide the majority of the suitable nursery habitat for penaeid prawns *viz* St Lucia, Richards Bay and the Mhlatuze estuary (Demetriades and Forbes, 2003). This could significantly reduce the effort required to determine estuarine suitability in terms of its nursery function in certain regions. In most regions the exact role of many estuaries in terms of nursery function to various species is relatively unknown.

  Estuarine mouth conditions largely determine the ability of species to recruit to estuaries and also play a role in the emigration of species back to the marine environment. It is not only open mouth conditions that determine recruitment success as recruitment can also occur due to berm overwash (*e.g.* Cowley *et al.*, 2001). Regular mouth condition information is available for only a few estuaries along the South African coastline. The water level gauge network required to characterise estuarine mouth conditions does not exist. Previous observer programs also have only met with partial success. Thus a more directed effort is required to characterise mouth condition in South African estuaries.

- **Freshwater inflow rates**[34] to the marine environment from estuaries, that primarily are a function of mouth conditions and freshwater inflows into the estuary:

  Mouth condition, *i.e.* the extent to which the mouth is open, restricted or closed obviously plays a critical role in estimating freshwater-derived inflows to the marine environment, particularly along the warm temperature and subtropical coastlines where there are many small temporary open-closed estuaries. The adequate knowledge of mouth condition in these systems is limited, despite a number of detailed studies (Bell *et al.*, 2001).

[34] Although not the focus area of this study, anthropogenic influences also include increases in flow due to, for example, waste water treatment plants or inter-basin transfers. There are several large inter-basin transfer schemes already in operation of which the Orange-Sundays-Great Fish River Water Transfer Scheme is the largest. In this scheme water is transferred through about 100 km of tunnels and canals from the Orange River to the Sundays River and thence to the Great Fish River (Davies and Day, 1998).

The other factor determining freshwater-derived inflows to the marine environment is the rate of freshwater inflow to the estuaries. Ideally daily freshwater inflow rate estimates are required, however typically only monthly mean freshwater inflow rates to estuaries are available. (The most comprehensive data set presently available is that of an approximate 20 year measured/simulated time series of monthly mean flows for the estuaries of northern KwaZulu-Natal. If these data are to be used in anything more than the simplest of analyses, they will need to be supplemented by daily measurements/simulations or scenario-based estimates of flood hydrographs.)

In general the freshwater inflow rates to estuaries in South Africa are poorly characterised at the temporal scales required to assess the freshwater-derived fluxes into the marine environment. Typically these freshwater inflow rates are only simulated for long periods when required for Reserve Determinations on specific estuaries.

- **Nutrient fluxes into the marine environment:** These nutrient fluxes include both dissolved nutrients and POM being exported to the marine environment. Presently there is a dearth of such data. In a number of systems sufficient data exists for dissolved nutrients but little data exists for POM. An assessment of the nutrient data available for the estuarine systems of KwaZulu-Natal has been undertaken (van Ballegooyen and Gulekana, 2005) Given the paucity of data available to adequately characterise the nutrient fluxes into the marine environment of the Natal Bight an approach has been suggested (van Ballegooyen and Gulekana, 2005) whereby estimates of nutrient and sediment fluxes to the marine environment are obtained by attempting to classify estuaries according to the attributes that determine nutrient fluxes, sediments fluxes, *etc.* to the marine environment and then extrapolating detailed information available for one or more of the estuaries in each classification to provide appropriate estimates for the other estuaries in each classification (WL | delft hydraulics, 2003).

  As noted elsewhere in this report, it is not always clear to what extent (if at all) there has been a reduction of nutrient loads into the marine environment. This also needs to be resolved.

- **Sediment fluxes into the marine environment:** Similarly, while there may be more detailed information for some estuaries, *e.g.* Thukela (Beck *et al.*, 2004), the sediment fluxes from most estuaries into the marine environment are generally poorly known. An approach based on the classification of estuaries with respect to their sediment discharges to the marine environment may prove to be useful in providing the necessary first order estimates for the region(s) being assessed.

The above measurements all are aimed at characterising the **nature of freshwater-related fluxes into the marine environment**, a necessary precursor to any study assessing the freshwater requirements of the marine environment.

Also of importance is **the transport, dispersion and ultimate fate of freshwater-related fluxes upon entering the marine environment** from estuaries (*i.e.* nutrients, sediments, low salinity plumes, *etc.*). This can be assessed using a combination of measurements and hydrodynamic and water quality modelling in the marine environment.

6.4.1 Potential data sources to characterise freshwater-related fluxes into the marine environment

The **relative importance of terrigenous and oceanic sources of nutrients in the various food chains** may be resolved using stable isotope analysis. Stable isotope analyses have been undertaken for zooplankton, fish eggs and adult fish off KwaZulu-Natal, in an effort to determine whether there is a greater terrestrial signal during "wet years". However, to date, these have only been undertaken for "normal" years. Similar analyses also can be undertaken for other species.

The **macro-sedimentary environment** along the South African coast has been fairly well described, particularly in the KwaZulu-Natal region (*e.g.* Flemming and Hay, 1988; Smith *et al.*, 2006). Recent depositional zones have been sampled at a number of locations on the continental shelf of KwaZulu-Natal (*e.g.* off the Mhlanga River, Illovu River) as part of a study to assess potential long-term accumulation of contaminants in these offshore sediments (Carter, *pers comm.* and Connell, *pers comm.*). Similar measurements of offshore sediments should also be available from surveys undertaken by the Council for Marine Geoscience, Marine and Coastal Management, universities, *etc.*

Sediment particle size data exist for many estuaries and certainly for many coastal regions surrounding estuaries, however these data are distributed through a number of research organisations and will need to be collated for use in this or similar studies.

Measurements of **temperature, salinity, turbidity and frontal structures** are available from a number of hydrographic cruises along the South African coast. These data, where in existence, are likely to be contained within the South African Data Centre for Oceanography. (SADCO). Despite efforts by SADCO collate time series measurements of interest in the marine environment, other project-specific time series measurements whether undertaken for research or commercial purposes, are unlikely to be located in SADCO. A number of remotely sensed **infra-red and ocean colour imagery** data sets are available for the south African coastline, however these data are typically project -specific and may not provide the regular images required to adequately characterise the temperature, turbidity (sediment) and biomass characteristics of both nearshore environments and river plumes in the offshore zone. In the case of ocean colour images it is highly likely that substantial re-processing of images will be required.

If the freshwater-related fluxes into the marine environment are relatively well-known, it will be possible to characterise the transport, dispersion and ultimate fate of freshwater-related fluxes entering the marine environment from estuaries (*i.e.* nutrients, sediments, low salinity plumes, etc) through **hydrodynamic and water quality modelling of both nearshore and offshore environments**. The requirements for such a modelling exercise are detailed in van Ballegooyen and Gulekana (2005).

6.4.2 Measurement techniques to obtain to characterise freshwater-related fluxes into the marine environment

Potential measurement techniques to obtain the relevant data are listed below. The role of hydrodynamic and water quality modelling in providing information at the relevant temporal and spatial scales is included. Further observational data are required of:

- **Estuarine habitat**: The characterisation of estuarine health in terms of their ability to fulfil a nursery function requires a complex set of measures. These are typically assessed during the RDM process and are not further discussed here.
- **Mouth Conditions:** The assessment of mouth condition typically requires water level recordings in the estuary that will indicate whether the estuary mouth is open or closed. Beck *et al.* (2004) recommend that water level recorders are placed in all temporary open-closed systems of importance along the South African coastline. As water level recordings will not indicate outflows from a perched estuary and/or berm overtopping, ideally water level recordings will need to be supplemented by an observer program. In the absence of the above observations, a knowledge of flows and metocean conditions (daily) could be used to help characterise mouth states (Theron and Bergman, 2007).
- **Cueing effect**: Evidence of flow into the marine environment is required for a cueing effect to exist. The inflow could be direct inflow from an estuary or seepage through a berm. Flow and mouth condition can be used as a proxy measure for cueing effect and, as indicated above, this would require flow gauges, water level recorders and/or daily observations of mouth condition). Furthermore the likely extent and duration of the cueing effect could be characterised using estimated river outflows and nearshore modelling of metocean conditions.
- **Distribution of dissolved nutrients in the marine environment**: A nitrate probe mooring/profiler could be deployed to supplement a) standard surveys of nutrients concentrations in the marine environment and b) the time series measurements required to characterise estuarine fluxes of dissolved nutrients into the marine environment. Where dissolved nutrients are an overriding factor in phytoplankton production chlorophyll-a measurements can also be used as proxy for dissolved nutrients, however one would need to discern the influence of dissolved nutrients of terrestrial and oceanic origin. Typically stable isotope analysis is used to make this distinction.

- **Distribution of POM in the marine environment**: A rough characterisation of POM in the marine environment can be obtained using remote sensing techniques (e.g. using a visual wave band), however such data will not be quantitative but rather only indicative of POM concentrations near the sea surface.

- **Fronts, temperature, salinity and turbidity**: Flow and mouth condition can be measured as a very rough proxy for determining plume extent and consequently frontal features, temperature, salinity and turbidity associated with riverine/estuarine inflows to the marine environment. These could be more accurately characterised using flow and mouth condition data as inputs to a hydrodynamic model to better characterise the frontal features and plume extent both temporally and spatially. Specifically these model outputs could demonstrate the existence of, or the lack of, connectivity of estuaries in a region. However a relatively robust characterisation of the duration and extent of these features requires additional measurements to calibrate/verify the models. Such data should include:

  - **Salinity, temperature and turbidity profiles** for selected periods using conductivity, temperature and depth (CTD) and optical backscatter (OBS) instruments, *in-situ* temperature, salinity and turbidity profilers and/or moorings (*e.g.* thermistor chains, OBS instruments, moored buoys, *etc*) to provide time series at the required locations.

  - **Remote sensing techniques**, *e.g.* ocean colour, infra-red and visual wave bands. Such data exist for the South African coastline (*e.g.* a seven year set of 1 km resolution ocean colour remote sensing images exist for the South African coastline (LeMont, UCT, *pers comm.*)), however it will be difficult to provide quantitative measurements of biomass and sediments from these images that are required to develop quantitative relationships between years of low and high inflows to the marine environment and parameters such as biomass (phytoplankton) and sediments.

    Figures 15a and b are images in visual wave bands indicating chlorophyll-a concentrations (biomass) in the marine environment due to upwelling of nutrient-rich waters in the vicinity of Richards Bay (*i.e.* the azure coloured waters extending southwards across the Natal Bight). Figures 16a and b indicate two consecutive days during which there were strong river inflows into the same marine environment (albeit during the "dry" winter season). These images indicate a clear reddish brown discolouration of the waters near the Mfolozi, Mhlatuze and Thukela estuary mouths. However it is not clear to what extent the discolouration on a larger scale is due to sediments or the presence of chlorophyll-a. Also of relevance is the rapidity with which the discolouration of the waters changes over a couple of days.

    Infra-red imagery will not be useful in the north-eastern East Coast region as the water temperature of the freshwater-related inflows to the marine environment and those prevailing in the nearshore and offshore environments are similar. However such imagery may be useful on the West Coast where significant temperature

differences exist between riverine and estuarine inflows and those prevailing in the marine environment (*i.e.* river inflows are warm in summer when the water temperatures in the marine environment are at their lowest due to active upwelling, while in winter the riverine/estuarine inflows are cold when upwelling in the marine environment is less active, resulting in generally higher sea surface temperatures in the inshore region.)

- **Sediment particle size:** Shoreline sediment size data have been collected at numerous sites, however these need to be collated in a centralised database if they are to be of any use. Extensive offshore sediment surveys are unlikely to be undertaken unless for other reasons, (*e.g.* offshore mining, *etc*). Such data need to be collated wherever in existence.
- **Sediment deposition:** Aerial photographs exist for shoreline erosion/accretion studies, as do beach surveys at a number of locations (*e.g.* Theron, 2003; Theron *et al.*, 1991), however limited data exists for sub-tidal deposition of sediments. Where in existence, these data need to be collated from existing sources.



Figure 15: Ocean colour (visual band) images showing the biomass (downstream of the upwelling that occurs in the vicinity of Richards Bay. (Source: http://visibleearth.nasa.gov)



Figure 16: Ocean colour (visual band) images showing discolouration of the offshore waters on two consecutive days during which there were strong river inflows into the marine environment (albeit during the "dry season"). (Source: http://visibleearth.nasa.gov)

To assess the potential importance of submarine groundwater discharge to the marine environment it is essential to map the possible spatial extent of potential groundwater dependant marine ecosystems. This requires that:

- possible submarine groundwater discharges are identified country-wide to provide an insight into the potential extent of impacts associated with reduction of submarine groundwater discharge to the marine environment. This requires both spatial data on aquifer type and temporal data on the nature of aquifer recharge (*i.e.* mapping of recharge characteristics);
- guided by these data, follow-up surveys and field work be undertaken to confirm the identified location of submarine groundwater discharges and identify ecosystems where submarine groundwater discharges may be important;
- the probable magnitude of nutrient inputs into marine environments for the various submarine groundwater discharge locations and types, be quantified..

On a local and regional scale, firm estimates of the location and magnitude of groundwater flow are scarce because of the difficulty of measuring submarine groundwater discharges and because the sites of submarine groundwater discharges often are not obvious. Several potential indirect indicators of the presence of freshwater submarine discharge have been suggested but have not been widely applied (UNESCO, 2004) where the freshwater may be identified by its colour, temperature, salinity of some other geochemical footprint. Methods that have been utilised to measure submarine groundwater discharges to the marine environment (*e.g.* Zektzer *et al.*, 1973, UNESCO, 2004) include:

- Methods founded on the *investigation of the coastal drainage* area that endeavour to estimate submarine groundwater discharge locations and flows by analysing the structural and general hydrogeological conditions of the adjacent coast area (*i.e.* presence of coastal ponds or unconsolidated coastal bluffs, which may maintain a high hydraulic head near shore) and/or by assessing coastal vegetation (*e.g.* growths of freshwater coastal vegetation) for evidence of groundwater presence and potential inflows to the marine environment (UNESCO, 2004; Colvin *et al.*, 2003, 2006). It has also been suggested that the presence of barite, oxidized shells, or beach rock may indicate the occurrence of groundwater discharges (UNESCO, 2004).
- Methods founded on *investigations in the marine environment* such as the measurement, both in the marine waters and at the sediment water interface, of temperature and salinity anomalies, changes in the chemical composition (*e.g.* high levels of nutrients such as nitrates, *etc*) and the use of tracers such as such as 222Rn and CH_4. The conservative nature and short half-life of 222Rn (3.83 days) makes it ideal for tracing groundwater discharges to the marine environment. Although CH_4 has other sources and sinks in the marine environment, together with 222Rn, it is effective in tracing submarine groundwater discharges (Bugna 1995, Cable *et al.*, 1996). Elevated levels of radium, hydrogen sulfide or carbon dioxide may also be indicative of a submarine groundwater discharge. Evidence of groundwater-dependant marine ecosystems (*e.g.* indicated by

unexpected algal growth) are likely to be one of the best measures of submarine groundwater discharges as these are the very ecosystems that would be of concern should there be significant reductions in the quantity or quality of submarine groundwater discharges into the marine environment.

The Catchment2Coast research initiative (Monteiro and Matthews, 2003) has a significant groundwater component to the study. The methods used and learning from the Catchment2Coast project should be utilised to determine how best to proceed. At present there is seemingly no specific initiative to investigate the ecological impacts of groundwater in the South African marine environment. The recent WRC project to assess groundwater dependant ecosystems (Colvin *et al.*, 2003, 2006) did not consider the impacts of submarine groundwater discharges in the marine environment in any great detail, however proposals exist to assess the role of groundwater in estuarine ecosystems.

7. Preliminary Assessments

7.1 Subtropical Region

The South African coastline, being one of the smoothest and least convoluted (*i.e.* with the lowest fractal index) in the world and being swept by strong currents, has relatively few habitats suitable as spawning and nursery areas. The KwaZulu-Natal coastal and shelf waters between Durban and Richards Bay, however, are relatively insulated from the direct effects of the strong offshore currents in this region (*i.e.* the Agulhas Current). The significant retention and concentration mechanisms operating both in the nearshore and shelf regions of the Natal Bight, together with upstream upwelling node just north of Richards Bay, have resulted in the Natal Bight being identified as one of four southern African spawning grounds (mainly fish) of importance (Hutchings *et al.*, 2002).[35] However, conditions north of St Lucia and south of Durban are somewhat different in that there is greater exposure to the Agulhas Current and a much shorter residence time of coastal and shelf waters. Estuarine inputs of freshwater, nutrients and sediments to the coastal region south of Durban, due to the greater influence of the Agulhas Current, are unlikely to create a continuous habitat (that is similar to that of the Natal Bight) anywhere except in the very nearshore and surf zone. Modelling undertaken in this region indicate that indeed there is a significant residence time of river inflows confined to the nearshore region along this section of the coastline (Monteiro *et al.*, 2002).

[35] The investigation of such spawning and nursery areas is critical as these are the areas that constitute habitats to the early larval stages of most species where survivorship is likely to have its greatest dependency on environmental conditions, in particular those that may be changed due to a reduction of freshwater inflows to the marine environment.

The freshwater inputs to the KwaZulu-Natal coast comprise inflows from many both small and larger estuaries. No one estuary, with perhaps the exception of the Thukela River, is likely on its own to have a substantial influence on the marine environment.

The assessments from the initial workshop are summarised below for this Subtropical Region.

7.1.1 Ecological response to a reduction in freshwater-related fluxes to the marine environment

The workshop assessment of the potential effects of changes in freshwater inflow to the marine environment is summarised in Tables D.1 and D.2 (Appendix D). The sensitivity of the various ecological response categories to the various drivers that could change substantially with a reduction of freshwater inflow to the marine environment, are summarised in Table D.1. Table D.2 provides a degree of detail on the nature of the likely response (*i.e.* the species of relevance and the nature of the effect).

The ecological response categories most affected by reductions in freshwater flow are expected to be fish and benthic invertebrates. This is borne out by the fact that benthic invertebrates and fish were used to assess potential changes associated with various dam development options on the Thukela River (Louw, 2003). These two categories are expected to have a moderate to strong response to most of the drivers listed. Phytoplankton, benthic algae and holo-zooplankton also indicate a fairly strong response but only to a more limited range of drivers, (*e.g.* dissolved nutrients, turbidity, *etc*).

The only driver considered having little or no impact on ecological response in this region is temperature as the temperature of the estuarine inflows and those in the marine environment are largely similar.

Nursery function

Availability of a nursery function for marine biota with an estuarine dependency, firstly requires that the estuary is accessible at the times needed (*i.e.* the mouth needs to be open for both recruitment and emigration) and, secondly, that the health of the estuary is such that the estuary remains an appropriate habitat for estuarine dependent marine-biota (*i.e.* the relevant physico-chemical distributions and required habitat-forming flora and fauna are present). Thus both "estuarine mouth condition" and "estuarine habitat suitability" are of relevance here.

Often only one or a few of the estuaries along a particular stretch of coastline may be able to provide a suitable estuarine nursery habitat for a particular species. That species, at critical periods of its life cycle, may be highly sensitive to closed mouth conditions occurring even for only one of the estuaries potentially providing such a nursery function. Along the KwaZulu-Natal coastline only three systems provide the majority of the suitable nursery habitat for penaeid prawns *viz* St Lucia, Richards Bay and the Mhlatuze estuary. Penaeids have been recorded in

many other estuaries but are not found in high numbers and therefore these are not considered to constitute significant nursery areas (Demetriades and Forbes, 2003). Penaeid prawns therefore are particularly vulnerable to the loss of one or more of these nursery areas, either due to reduced access or degraded estuarine health (*e.g.* the removal of mangroves that have been recognised as particularly important during juvenile development of shallow water penaeids (Weerts *et al.*, 2003)).

Similarly, changes in freshwater inflow to estuaries of sufficient magnitude to affect the frequency and duration of mouth opening or closure are expected to have a significant impact on estuarine dependant fish and consequently on any fishing activities based on these species. Recruitment to estuaries does not necessarily require open mouth conditions as it has been shown that some estuarine dependant nearshore fish species are able to enter closed estuaries via berm overtopping both in this region (Perisinotto *et al.*, 2003) and further afield (*e.g.* Bell *et al.*, 2001; Cowley *et al.*, 2001).

Cueing Effects

Associated with the estuarine nursery function is the role of possible cueing effects. The strength of these cues will ultimately dictate how many individuals of these species will recruit into the marine fisheries. The exact nature and physiological basis of this cueing effect is not yet understood, although evidence exists that it may be olfactory in nature (*e.g.* Strydom and d'Hotman, 2005). While this effect has been investigated in some detail for estuarine dependant fish in the warm temperate region (Strydom and d'Hotman, 2005) we are not aware of any substantive studies of potential cueing effects in the subtropical region. Similar cues may exist for invertebrates (*e.g.* prawns, *Varuna litterata*), however there is evidence that indicates that prawns do not necessarily require such cues (A. Forbes, *pers comm.*). For example, prawns were still present in the St Lucia narrows during periods when the lake was hyper-saline, i.e. > 35 psu.

Similarly, freshwater inputs to the marine environment may provide spawning cues. In this regard a knowledge and understanding of the *spatial extent and persistence* of the cues is important.

Spawning and survival of the early life stages

It is the habitat requirements for successful spawning and survival of the early life stages that will provide the greatest clues to how changes in freshwater flows to the marine environment and associated changes in habitat/drivers, are likely to impact upon ecosystems. A 17 year long monitoring program along the KwaZulu-Natal coastline has shown a strong positive correlation between river flow and fish egg abundance, *i.e.* there is evidence of increased spawning intensity during years of increased freshwater inflow to the marine environment. Presumably this will also result in conditions for enhanced survivability of fish larvae.

Nutrients

Along the KwaZulu-Natal coast the coastal and shelf waters are largely oligotrophic (Carter and D'Aubrey, 1988; Meyer *et al.*, 2002) with significant input of nutrients onto the shelf occurring only in the vicinity of Richards Bay. The nutrient supply associated the freshwater inflows thus

are likely to be of greater importance in such an oligotrophic system. Both dissolved nutrients and nutrients in the form of particulate organic matter from terrigenous sources are of relevance here. Their role in the KwaZulu-Natal ecosystem is dealt with in greater detail in the prawn and fish studies undertaken for the Thukela RDM study (Louw, 2003). These are summarised below.

Although the nutrients from terrestrial run-off have been reported to play only a small role on the nutrient distribution of the Natal Bight (Carter and D'Aubrey, 1988), there are indications that they may play a significant role, particularly in the central region of the Natal Bight where particularly high phytoplankton concentrations have been observed on a number of occasions (Carter and Schleyer, 1998; Ryther *et al.*, 1966). In nearshore waters the nutrients from run-off are expected to play an increasingly important role, particularly that of POM. To date there have been no studies specifically directed at determining the relative importance of nutrients of terrestrial and oceanic origin. Further, while there may have been significant reductions in freshwater flow to the marine environment, due to changing land use practises and effluent discharges into estuaries it is not clear whether there has been a net reduction in nutrient inputs to the marine environment over time.

The relative importance of terrigenous and oceanic sources of nutrients in the various food chains may be resolved using stable isotope analysis. Stable isotope analyses have been undertaken for zooplankton, fish eggs and adult fish off KwaZulu-Natal, in an effort to determine whether there is a greater terrestrial signal during "wet years". However, to date, these have only been undertaken for "normal" years. Similar analyses still need to be undertaken for a period when there has been increased freshwater inflow to the marine environment.

Sediments

The sediment inputs to the marine environment are important for two reasons, namely due to their role in:

- the creation and maintenance of physical habitat in the marine environment;
- shoreline erosion and accretion and consequently the maintenance of recreational facilities (sandy beaches, *etc.*) and potential impacts on coastal developments (shoreline erosion and associated set-back lines).

Potential sources of sediments in the marine environment along the KwaZulu-Natal coast and further offshore are fluvial discharge, coastal and submarine erosion, aeolian transport, biogenic products and *in-situ* authigenic mineralisations. Of these potential sources, authigenic mineralisations and aeolian inputs are negligible, while the sediment supply from coastal and submarine erosion is not significant on the shorter time scales of interest here.

The most important source of sediments in this region is fluvial discharge, *i.e.* predominantly inorganic sediments loads that enter the marine environment as bedload and suspended sediments. The annual terrigenous sediment input for coastal Natal is estimated to be about 20×10^6 m^3 (or roughly 30 x 10^6 tonnes). Assuming that the bedload makes up at least 12% of

this total (Rooseboom, 1982 as quoted by Flemming and Hay, 1988), then the annual suspended load and bedload inputs are 17.6×10^6 m^3 and 2.4×10^6 m^3, respectively. (Assumed sand percentages of approximately 15% have been used in more recent studies (Dunckley *et al.*, 1998)). The Tugela River alone is estimated to have an annual sediment yield of between 5.6×10^6 m^3 (Flemming and Hay, 1983, 1984) and 6.8×10^6 m^3 (Dunckley *et al.*, 1998), i.e. roughly 10.3×10^6 tonnes to 15.4×10^6 tonnes per annum. The estimated annual sediment loads for the various major sources along the northern KwaZulu-Natal coastline are given in Table 6.

The second most important source of shelf sediments is the biogenic pool, comprising mainly sand- and gravel-sized bioclastic debris estimated to be 0.18×10^6 m^3 per year (Flemming and Hay, 1988). Thus, overall, the KwaZulu-Natal continental shelf is dominated by terrigenous sediments with biogenic material playing only a small role.

Development of dams on rivers are likely to have a winnowing effect on the sediments, the heavier sediments being deposited in the dams while the finer sediments could bypass the dams during floods and be discharged into the marine environment. Whether dam developments significantly change the coarser sediments reaching the marine environment will partially depend on how far upstream the dam is located and the relative size of the dam (*e.g.* relative to mean annual runoff).

Table 6: Estimated annual sediment loads for the various major sources along the northern KwaZulu-Natal coast.

Source	Annual sediment load (m^3 /year)
Thukela (Tugela)*[1]	6 790 000
Nyoni*[2]	Negligible
Matigula*[2]	173 400
Siyaya*[2]	Negligible
Mlalazi*[2]	40 740
Mhlatuze*[3]	237 000
Mfolozi*[4]	1 500 000

*[1] from Dunkley *et al.* (1998) based on Rooseboom (1992)
*[2] estimated based on Thukela sediment loads (from Dunckley *et al.*, 1998)
*[3] from Schoonees *et al.* (1999)
*[4] from Mason (1992).

As noted previously there is a strong perception that siltation and sedimentation have had the most detrimental effect on (certainly KwaZulu-Natal) estuaries (*e.g.* Begg, 1978, 1984). Reference is often made to the "sanding up" at estuary mouths as well as "silting up" in middle and upper reaches. Both could be attributable to reduced flows, certainly sedimentation of estuary mouths probably results from wave driven sediment transports and flood tide deltas building up (reduced river flow) rather than increased river loads. This in turn could result in siltation further up the system (reduced tidal prisms, *etc.*). There is an obvious connection between river flow and purging of estuaries of silt accumulations, however that bad catchment management and poor

land use practises resulting in increased erosion and greater silt (and sediment) loads in South African estuaries (KwaZulu-Natal and Eastern Cape) is widely accepted as fact and also that these sediment loads are being delivered into our marine environments. However, there remains significant uncertainty as to whether sediment loads into the marine environment have increased or decreased over time.

The macro-sedimentary environment along the KwaZulu-Natal coast has been summarised by Flemming and Hay (1988) while, more recently, descriptions have been provided of the localised sediment transport regimes surrounding Durban (CSIR, 1995) and Richards Bay (Schoonees *et al.*, 1999). The distribution of the sediments from Cape Vidal to Durban is given in Figure 17 (Flemming and Hay, 1988). The bulk of sediments on the shelf (> 75%) comprise sand (63 µm-200 µm) with gravel and mud restricted to well-defined localities. The gravel and coarse and very coarse sand fractions are concentrated around a mid-shelf dune ridge and where the bedrock outcrops through the surficial sediment cover on the outer shelf. The medium and fine sands are derived from the rivers feeding the area, as are the muds. Fleming and Hey (1988) state that the fine sediments carried in suspension do not appear to deposit to any large degree on the shelf and are probably being transported to the deep ocean.

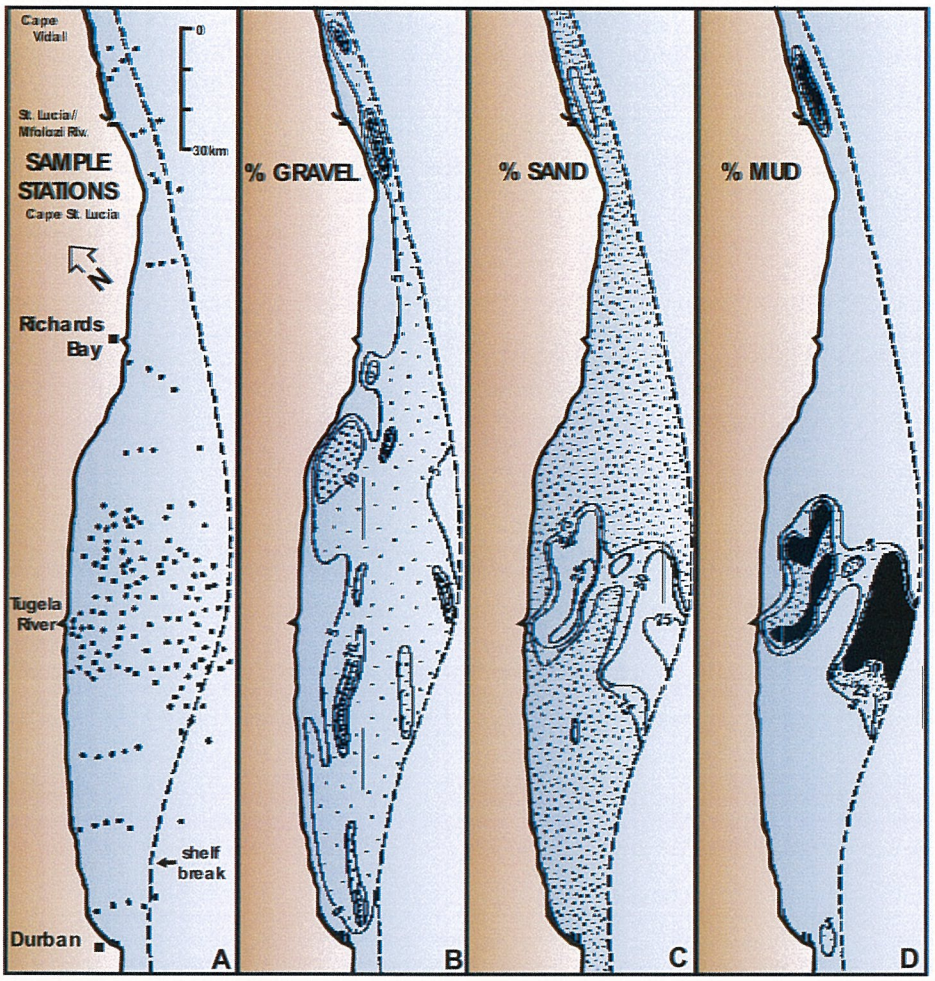


Figure 17: Sediment distribution patterns on the central KwaZulu-Natal continental shelf (after Flemming and Hay, 1988)

True muds are rare along the entire coast of southern Africa, despite the relatively large annual inputs. The mud deposits that do exist in this region are spatially confined and seem to be derived mainly from episodic floods. Two noticeable mud depocentres on the KwaZulu-Natal shelf are off the Thukela River (Figure 17) and off the Mfolozi /St Lucia River confluence. Additional deposition zones have been identified (*e.g.* off the Mhlanga River) and recently been sampled (Connell, *pers comm.*) and an attempt made to date the sediments. The mud deposits off the Thukela River, however, are reported to contain only minor proportions (10%) of the estimated local inputs (Felhaber, 1984) with most of the suspended sediments being exported from the region over time. Furthermore there is strong evidence that further offshore the deposits of mud in the vicinity of the Thukela River are not recent (Felhaber, 1984). Biogenic carbonate concentrations are highest in the coarser sands of the midshelf aeolianite ridge and lowest in the muds and very fine sands.

The bedforms over the shelf and shelf break give an idea of the sediment transport processes operating in this region. While there is clear indication of bedforms associated with strong uni-directional flows at the shelf break of the Natal Bight (Flemming and Hay 1988), there are large continuous tracts of sand with strong margins with rippled sediments in between that are observed on the shelf, that indicate the presence of strong wave-induced turbulence and oscillatory flows at the seabed with these effects extending to depths as great as 100 m. That a mud depocentre such as that off the Thukela River has been established in a shelf environment affected by strong wave action suggests that the muds are supplied in pulses of high concentration during seasonal river floods, that flocculation processes are important and that suspended sediment plumes most likely become trapped in eddies centred over the mud deposits.

In summary, the severe wave climate coupled with ocean currents evidently keeps most of the muds in permanent suspension, in which form they are exported from the shelf environment. Only in places where concentrated mud plumes get trapped in the low velocity centres of closed circulation/eddy systems or similarly quiescent regions can they settle out. From the above one can conclude that there is a high mobility of sediments on the shelf off KwaZulu-Natal, however on shorter time scales, significant accumulation of sediments is possible under more quiescent conditions and in protected locations.

In contrast, bedload sediments comprising the coarser sediments fractions have at least an interim "shelf life" before they are exported off the shelf. Flemming (1980, 1981) indicates that such bedload export from the shelf occurs at a number of places, one of these being the region ESE of the Thukela River mouth, the other in the vicinity of Cape Vidal. From the above one can conclude that there is a high mobility of sediments on the shelf off KwaZulu-Natal, however on shorter time scales, significant accumulation of sediments is possible under more quiescent conditions and in protected locations.

The **coarser sediments** are expected to play a "structural" role in that changes in these sediments are likely to lead to shoreline erosion and/or accretion. For, example, the greater length of the shoreline north of the Thukela is prograding (Cooper, 1991, Dunkley *et al.*, 1998), as evidenced by studies of aerial photographs and vegetation lines and fully developed dunes parallel to shoreline and set back from the present dunes. The bulk of the sediment supply for this shoreline accretion is from the Thukela River (Table 6), however other estuaries may play a significant but typically more localised role in shoreline dynamics. For example, for the coastline between the Matigulu mouth and the Mlalazi Mouth where Cooper (1991) reports a long-term net averaged rate of accretion of about 2-3 m per annum, there is strong evidence of a significant increment of beach-forming sediments from the Matigulu River that is a shallow bed-load-dominated river which introduces influxes of sand to the coast, particularly during floods (Cooper, 1991). Although there is a net accretion of the shoreline along this northern region of the Natal Bight, the actual rate of accretion varies enormously from year to year (In some years small net retreats have occurred due to episodic events like storms, floods or short term reductions in yield from the Thukela River).

While a number of studies have been undertaken of potential shoreline erosion and accretion (e.g., Cooper, 1991; Dunkley *et al.*, 1998; Theron AK, 2003), only the study by Dunkley *et al.* (1998) has explicitly addressed the potential consequences of the reduction of sediments inputs into the marine environment due to the reduction of freshwater inflows and dams developments. In this study, it was found that the historic rate of shoreline accretion would be reduced significantly (within 10 to 20 km north of the mouth). To date no study has addressed the potential impacts on a regional basis (*i.e.* regional impacts due to developments and water abstraction activities on one or more of the regions estuaries) or to determine the relative importance of the role played by sediment discharges from the various rivers and estuaries along this coastline in shoreline erosion and/or accretion.

The **finer sediments**, particularly the muds are expected to play a significant role providing appropriate physical habitats in the marine environment (*i.e.* by providing a substrate for colonisation by primarily smaller benthic organisms, invertebrates and benthic fish). Organic sediments also need to be considered where they, through their deposition on the seabed, help to create a physical habitat suitable for various marine organisms. As noted in Part I: Section 4.5.3, it is not only the ***quantity of sediment*** being discharged into the environment but also the ***nature or quality of the sediments*** (*i.e.* grain size distribution and organic content) that is of importance. The quantity of sediments discharged into the marine environment determines the potential spatial extent and depth of sediments providing a suitable habitat for marine biota, *i.e.* changes in the extent of suitable habitat. The grain size distribution and organic content, in turn, determines both the initial distribution and ultimate fate of the sediments in the marine environment and also whether the deposited sediments actually constitute a suitable habitat for the various life stages of marine biota under consideration. Similarly, the strength of flows leaving the mouth of estuaries determines the initial extent of the plume containing particularly the fine sediments and consequently, the initial distribution of muds in the adjacent marine environment. The persistence and spatial extent of the various marine sediments at various cross-shore locations largely determines whether the deposited sediments actually constitute a physical environment of significance. It is anticipated that in the long term, an increase in fine sediments could favour penaeid prawns and flatfish species, but be detrimental to invertebrate filter-feeders and ultimately the reef-dwelling fish species that prey on them. However, in the short term, increased turbidity would provide refuge and foraging area for many fish species (Lamberth, 2003).

On the KwaZulu-Natal coast the sub-adult and adult stages of shallow water penaeid prawns are expected to have physical habitat requirements based on sediment inputs into the marine environment. Changes in the aerial extent and composition of sediments are likely to influence the relative abundance and community structure of shallow water penaeid prawns (Demetriades *et al.*, 2000). For example, an increase in the area of fine sediment on the Thukela Bank could extend the potential area of prawn habitat (especially *P. Indicus*), however should nutrient inputs

decrease due to a reduction in freshwater inflows it could be that, despite an ostensible extension in the adult habitat, the populations may not increase (Forbes and Demetriades, 2005).

Evidence that increased fine sediments over the shelf would favour flatfish species in this region is provided by the observed increase in the abundance of flatfish after the massive inflow of sediments to the shelf region that occurred during the 1987 floods. After these floods new sediment deposition exceeding a thickness of many centimetres were observed in a water depth of approximately 50 m near the existing marine outfalls (Connell, *pers comm.*).

Prawn fishery

The life cycle of the shallow water penaeids in KwaZulu-Natal is succinctly described by Demetriades and Forbes in the Thukela study (Louw, 2003). Due to the short-lived nature of most species and the habitat requirements of the various life stages[36] (Figure 18) it was anticipated that they would provide a good indicator species for proposed changes of freshwater flow into the marine environment along the KwaZulu-Natal coastline (Demetriades, 2003).

[36] Most of these species inhabit shallow water, inshore, tropical and subtropical waters and have postlarvae and juveniles that have a preference for estuarine type environments. The life span of these species is generally short (generally one to two years). Adults are found in inshore marine waters. Copulation and spawning occur exclusively in the marine environment, occurring in the shallow waters of the continental shelf (between 15 m and 40 m) between Richards Bay and Zinkwazi off Kwazulu-Natal. Most species reach maturity at six months becoming increasingly fecund with further growth (a year old female may produce vast quantities of eggs at a single spawning and may also spawn more than once in a season). Upon release the eggs sink to the bottom and within 24 hours hatch into pelagic larvae that grow through a number of larval stages over the next three weeks culminating in the final planktonic stage, the postlarvae. Upon reaching suitable coastal nursery habitats (typically sheltered areas such as estuaries or seagrass beds), the postlarvae settle and adopt a benthic lifestyle. The young prawns move back to the marine adult habitat after maturing for approximately three months in these nursery areas.

It is clear that the different life stages have critical habitat requirements that differ somewhat. The nursery function or ***availability of a nursery habitat*** is critical to the ***postlarval stage*** that generally enters estuaries (recruitment) during July to September and remain there for 8 months (the juvenile prawns start leaving estuaries (emigration) during February to March). The nutrient requirements for the larval stage differ from the sub-adult and adult prawns. In the larval stage plant nutrients (primarily nitrates and phosphates essential for plant growth) are of importance as these support phytoplankton growth which is a major component of the diets of the planktonic larval prawns. For sub-adult and adult prawns, organic carbon availability is derived from both indirectly from the marine food chain beginning with phytoplankton production and directly via organic and detrital input from river flow. In addition, the sub-adult and adult stages may have a physical habitat requirement based on sediment inputs into the marine environment.

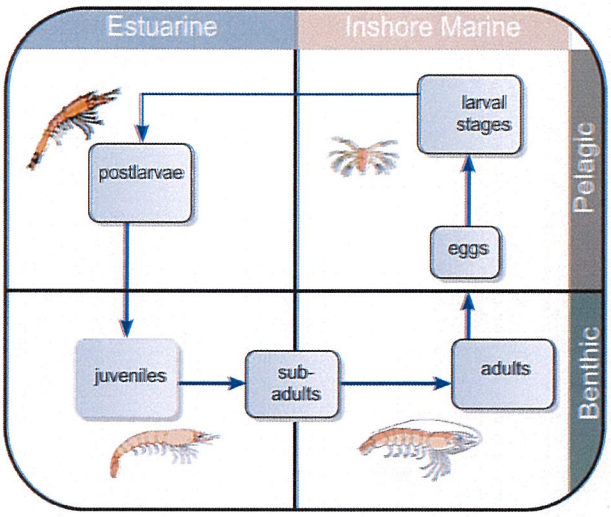


Figure 18: Life cycle of a typical shallow water penaeid prawn (adapted from Demetriades *et al.*, 2000; Demetriades and Forbes, 2003)

In the Thukela RDM assessment, the prawn catch was modeled as a function of an environmental index that was a linear combination of a ***nursery index*** and a ***nutrient index*** (see Part 1: Section Chapter 2.2.1 for details). The relative weighting of these indices were varied to obtain the best relationship between prawn catch and the overall environmental index and a log relationship was developed that that explained 77% of the variance of the prawn catch data in terms of the overall environmental index. Although the study indicated a clear and strong relationship between freshwater inflow to the marine environment, only a relatively insignificant change in the prawn fishery was predicted for the development scenarios proposed for the Thukela River.

Recreational and commercial line fishery

Conversely, no similar clear relationship catch and freshwater flow was anticipated for the fish species comprising the recreational and commercial line fishery due to the greater influence of other environmental variables, the relative longevity of the species considered (8-40 years compared to 18 months for penaeid prawns), noise from other environmental variables, varying levels of fishing effort, and the cumulative effects of recruitment and exploitation on different year-classes. In particular, the belief that the low degree of estuarine-dependency among the species caught by the boat-based line fishery, compared to the high dependency found in the shore-based, rock and surf fishery, would result in a poor relationship between flow and catch (Lamberth and Turpie, 2003) proved to be incorrect. Despite the "noise" there appears to be significant relationships between flow and catch for both fisheries (some are likely to be real but some may be the result of catches responding to other environmental variables, water temperature, current directions, which follow similar seasonal patterns to rainfall and flow).

The results of this study are described in detail in Lamberth (2003) and Lamberth and Drapeau (2007). A brief summary of the suggested relationships between freshwater dependant drivers (nutrients, turbidity, *etc.*) and the various fish species is provided below.

Analyses using cross-spectral analysis of flows versus Catch per unit effort (CPUE) data indicated correlation at periods of 11 to 12 months and over longer periods. The short term correlations were ascribed to a combination of increased nutrient and sediment inputs from the catchments, increased primary production and food availability as well as the effort patterns of the commercial fishery (increased food availability and turbidity tend to attract fish as well as other fishers who are aware of the aggregations that occur in response to these factors). The short term peaks in cross-spectral densities (1-2 months) for slinger, javelin grunter and rock-cods are ascribed to immediate responses to an increase in turbidity that promotes aggregation and catchability of these species. These aggregations would persist with increased food supply. The peaks in cross-spectral densities at 4 months for squaretail kob, dusky kob and poenskop are ascribed to the lag between flow events and associated increased nutrient inputs and subsequent increased productivity and eventual food/prey availability. The longer term response observed for javelin grunter, king mackerel, sea catfish and squaretail kob are seemingly related to long term wet and dry cycles, the catches being higher in wet years. Analyses of rock cod, slinger and squaretail kob CPUE indicated weak cross-spectral peaks at a lag related to the age-of-first-capture in the fishery. These seemed to indicate a relationship between wet years providing suitable conditions for spawning and survival and eventual recruitment into the fisheries a few years later. The weakness in using cross spectral densities is deemed to be due to the cumulative impact of fishery impacts and environmental factors other than those related to flow.

Analyses using General Linear Models between CPUE and monthly flow of the major systems all indicated significant relationships at zero or one month lags. The strongest relationships were between flow and the CPUE of redfish (slinger and santer) and poenskop where freshwater flow explained 67% and 59% of the variability in catch, respectively. Overall, with the exception of king mackerel, the strongest relationships were with the reef species that typically show a high degree of residency (non-migratory) and hence are unlikely to move in response to environmental changes. The more nomadic of the resident species (squaretail kob and santer) are less dependant on flow, possibly due to their more nomadic behaviour.

King mackerel respond to flow with a lag of approximately 10 months and 6 to 8 years (representing wet and dry cycles). The short term correlations with flow in KwaZulu-Natal are likely to be false due to the fact that recruitment into the fishery is related to good conditions for spawning and larval survival off Mozambique associated with freshwater inputs into the marine environment off Mozambique. Within a season enhanced production and associated increased prey availability due to increased flow off KwaZulu-Natal may result in increased catches of king mackerel during their migration southwards in response to the increased prey availability. Conversely, in the short term, weather and fishing conditions associated with higher freshwater inflows off KwaZulu-Natal could result in a decline in CPUE.

Squaretail kob that are endemic to southern Africa with a distribution range extending from Mozambique to Port Elizabeth (Fennessy and Radebe, 2000), respond to flow with a lag of 4.2 months, 3.5 years (roughly corresponding to age-of-first-capture) and 6 to 8 years. In the very short term, squaretail kob CPUE responds negatively to higher freshwater inflows due to deteriorating fishing conditions and fisher behaviour (*i.e.* the fishing fleet fishes elsewhere). The positive response to flow with a four month lag may partially be due to fishers targeting more effort on this species due to a known increase in catchability, but is considered to be primarily due to higher flows in the summer months following spawning (June to September on the Thukela Bank) that results in increases in nutrients, production and turbidity, all of which are conducive to larval and juvenile survival.

Ecological response to submarine groundwater discharges

In the subtropical region, *i.e.* the KwaZulu-Natal and adjacent Eastern Cape coastal region (formerly Transkei), the submarine groundwater discharges are expected to comprise predominantly surficial diffuse discharges (and deeper discrete groundwater discharges) characterised by a weakly bimodal to summer recharge. The freshwater and nutrient inputs via submarine groundwater discharge, whilst anticipated to be substantial, also are expected to be significantly less than that due to freshwater inflows from rivers. However, the high nutrient loads often typical of submarine groundwater discharges are likely to have a greater impact in the oligotrophic waters typical along the East Coast of South Africa than in the increasingly nutrient rich coastal waters of the South and West coast of South African. It is expected that during the low rainfall winter season the submarine groundwater discharges will play a greater role in supplying nutrients to the (nearshore) marine environment.

During this investigation, no studies were found that specifically address the role of submarine groundwater discharges in coastal ecosystems of the Subtropical coastal region of South Africa.

7.1.2 Socio-economic (resource utilisation) impacts

The following potential socio-economic impacts associated with reduced freshwater inflows to the marine environment, were identified:

- reduced catches in the prawn trawling/deep water crustacean fisheries;
- changes in the recreational and commercial line fishery;
- changes in the artisanal and subsistence fisheries, including filter-feeders;
- alteration of recreational beaches (shoreline erosion);
- potential impacts on coastal developments (shoreline erosion and associated set-back lines).

7.2 Warm Temperate Region

Due to time constraints the potential impacts on changes in freshwater inflows to the marine environment in the warm temperate region were not assessed in any great detail during the initial workshop.

7.2.1 Ecological response to a reduction in freshwater-related fluxes to the marine environment

The most affected ecological response categories are expected to be fish that are anticipated to have a moderate to strong response to most of the drivers listed. Phytoplankton, benthic algae and holo-zooplankton also indicate a fairly strong response but only to a more limited range of drivers, (*e.g.* dissolved nutrients, turbidity, *etc*).

The Eastern Cape Coast, extending from the Kei River to just of Port Edward comprises a rocky coastline with numerous small, sandy pocket beaches and many small estuaries that is swept by the Agulhas Current that normally lies close inshore in this region. In terms of ecological functioning and habitats, the influence of individual estuaries is likely to be of limited spatial extent, i.e. a ***more nodal response is anticipated*** This implies that the reduction of freshwater flow to an individual estuary and the consequent impact on the marine environment in this region, may be of greater relevance to its immediate surrounds than would be the case for a region such as the Natal Bight. Along the South Coast, from Cape Point to Algoa Bay, the coastline comprises a number of large bays separated by sweeping beaches and prominent headlands. The Agulhas Current lies far offshore while the flows over the adjacent shelf are largely wind-driven despite the strong influence of the Agulhas Current. Here the ecosystems functions largely on a coastal embayment scale, however further offshore the ecosystems are more spatially extensive. The influence of freshwater flows in this offshore zone are likely to be limited, except for perhaps sediment inputs.

On the Agulhas Bank, a large number of kob is taken by inshore trawlers, indicating the importance of inshore areas to many Agulhas Bank species. Yellowtail, geelbek, kob and elf are known to migrate moving eastward up the east coast onto the central Agulhas Bank or inshore. These migrations are believed to be linked with reproduction. Many species (*e.g.* elf, leervis, yellowtail, seventy four and red steenbras move north into the north-eastern East Cape or Natal waters to spawn between winter and early summer. White steenbras and the red stumpnose are known to move inshore into protected bays on the south coast to spawn (Buxton, 1990). The existence of certain substrates are associated with the spawning behaviour of some fish species, *e.g.* off the southeast Cape coast white steenbras *Lithognanthus lithognanthus* is known to spawn in July - August in the vicinity of mud banks deposited by rivers in this region (Bennet, 1993). A possible reason for this is the high concentration of microphytobenthic algae that are much more productive on mud banks than on coarse sand. These eggs and larvae are subsequently dispersed to nursery areas on the Cape Coast (Japp *et al.*, 1994). Rock pools and rocky gullies are

important to some inshore fishes, but few juveniles taken in fisheries occur there (Beckley, 1984; Smale and Buxton, 1989). Exceptions to this are black mussel cracker, blacktail and yellowbelly rock cod that form part of the inshore line fishery (Japp *et al.*, 1994).

Nearshore littoral areas are used by numerous teleost predatora, including juveniles of top predatory teleosts such as kob. Inshore areas are important nurseries for juveniles of large predatory fish, as well as some small species that feed mainly on small crustaceans such as mysids (*e.g.* Buxton *et al.*, 1984). Mysids are particularly important dietary items of smaller members of the nearshore fish community (*e.g.* Lasaik, 1983).

In their review of the fish resources of the Agulhas Bank, Japp *et al.* (1994) suggest that estuaries are not important for the life histories of most fishes of the Agulhas Bank, however Lamberth and Turpie (2003) have indicated that the economic value of the estuarine contribution to fisheries in this region is significant.

Associated with the estuarine nursery function is the role of possible cueing effects. The strength of these cues will ultimately dictate how many individuals of these species will recruit into the marine fisheries. Studies in this region indicate that the cueing effect may be olfactory in nature (Strydom and d'Hotman, 2005). Strydom and d'Hotman (2005) report a high abundance of recruitment-size, estuarine-dependent larval fishes in a surf-zone off Cape Padrone that is relatively remote from the nearest estuary. They postulate that the reason these estuary-dependent larval fishes accumulate in surf-zones may be related to the wait that accompanies cueing and transport mechanisms leading to recruitment[37]. Many estuaries in this region are subject to impoundments and water abstraction limiting the supply and frequency of cues and opportunity to recruit to the estuaries. Given the small size of South African estuaries, outflow plumes tend to be restricted to surf zone waters. However given the nature of alongshore flows, the alongshore extent of these cues may be significant.

Surf-zones are known to be productive areas that support high numbers of phytoplankton and zooplankton (McLachlan *et al.*, 1981) and have been shown to provide refuge habitat (Watt-Pringle and Strydom, 2003). Thus surf zones may provide ideal interim nursery areas for recruitment sized larval fish. This shallow water "cueing corridor" may explain the association of estuary-dependent larval fish with the surf zone waters. Should the above hypothesis be correct, it may be important to maintain freshwater inflows to estuaries and consequently to the nearshore environment not only to ensure "connectivity" of estuaries via this "cueing corridor" but also to ensure optimal surf-zone habitats (*e.g.* in terms of nutrients, phytoplankton production, zooplankton, *etc*). It is particularly the maintenance of appropriate low flow conditions that may be of importance here. Bell *et al.* (2001) have discussed the impact of waiting

37 Recruitment to estuaries does not necessarily require open mouth conditions as it has been shown that some estuarine dependant nearshore fish species are able to enter closed estuaries via berm overtopping or marine overwash (*e.g.* Bell *et al.*, 2001; Cowley *et al.*, 2001).

times[38] in the surf zone on survival of larval fish, indicating that the exponential nature of this relationship implies a very low survival rate for long wait times in the surf zone.

The effect of potential impacts of changes in sediment discharges to the marine environment on shoreline erosion and accretion is largely unknown. Studies, where they exist are likely to be focussed on only localised consequences.

Ecological response to submarine groundwater discharges

In the warm temperate region comprising the South Coast and the westernmost section of the East Coast, the submarine groundwater discharges are predominantly surficial diffuse discharges to the east of Port Elizabeth with deeper discrete discharges occurring east of Port Alfred. The recharge is expected to be bimodal to weakly bimodal towards the eastern extremity of the region. West of Port Elizabeth, the submarine groundwater discharge comprises predominantly discrete discharges characterised by winter recharge west of Cape Agulhas and year round recharge between Cape Agulhas and Port Elizabeth (Figure 4). The freshwater inflows from both submarine groundwater discharges and estuaries/rivers consequently is expected to be less seasonal that for the other coastal regions. If groundwater plays a role in coastal or nearshore ecosystems, it is expected to be localised and fairly limited. However it should be noted that the many coastal embayments along the South Coast result in sheltered marine environments, where evidence of any freshwater inputs into the marine environment is likely to be more persistent. The sandy beaches on the south-east coast may have an ecology that is strongly groundwater dependant, *e.g.* there are significant Table Mountain group discharges in the Coega region and the submarine groundwater discharges originating in the dune fields in this region are considered to play a significant role in the surf-zone ecology.

The only detailed studies located for direct groundwater discharge in the marine environment in this region are those undertaken in Algoa Bay. These studies assumed the nitrogen concentration in the submarine groundwater discharge to be approximately 190 $\mu M/\ell$ (Campbell and Bate, 1991). These studies show the local effects of groundwater in the surf-zone to be a significant (Campbell and Bate, 1998) source of nitrogen to the surf diatom *Anaulus australis*. Campbell and Bate (1991a) report that the standing stocks of surf diatoms are proportional to the amount of nutrient (N) entering the surf zone from the adjacent Alexandria dune field. Surf diatoms are an important source of food to animals living in the surf-zone such as mysid shrimps that feed extensively on the surf-zone diatom *Anaulus australis* (Webb *et al.*, 1987; Webb *et al.*, 1988; Wooldridge, 1989) as does the penaeid prawn *Macropetasma africanus* Balssam (Cockroft and McLachlan, 1986). Both the distribution pattern of *Gastrosaccus psammodytes* (Wooldridge, 1989) and the beach filter feeder *Donax serra* Röding (Donn *et al.*, 1986) were shown to be linked to the distribution of *Anaulus australis*. The surf mullet *Liza richardsonii* Smith feeds directly on the floating cells (McLachlan and Lewin, 1981). Surf diatom accumulations have been reported from

[38] Waiting time here refers to the time that larval fish have to wait before there is an opportunity to recruit to an estuary either through and estuary mouth opening or a berm overtopping event.

surf-zones of suitable beaches at Macassar, Struisbaai, De Hoop, Vleesbaai, Glentana, Wilderness, Sedgefield, Buffalo Bay, Oyster Bay and Cintsa beaches, South Africa (Campbell and Bate, 1991) (http://www.upe.ac.za/botany/surfdiat/whatare.htm). If many such or similar groundwater dependant marine ecosystems exist along the South African coastline, groundwater could be considered to play significant role in meeting the freshwater requirements of marine systems, particularly those of the nearshore zone.



Figure 19: Groundwater discharge observed in the warm temperate zone close to Stilbaai (source: S. Lamberth)

7.2.2 Socio-economic (resource utilisation) impacts

The following potential socio-economic impacts associated with reduced freshwater inflows to the marine environment, were identified:

- changes in the recreational and commercial line fishery;
- changes in the artisanal and subsistence fisheries, including filter-feeders.

There is less certainty around potential impacts such as:

- alteration of recreational beaches (shoreline erosion);
- potential impacts on coastal developments (shoreline erosion and associated set-back lines).

7.3 Cool Temperate Region

7.3.1 Ecological response to a reduction in freshwater-related fluxes to the marine environment

On the West Coast, the more limited number of rivers and estuaries and their relative remoteness from one another suggest that ***a nodal assessment approach is required.*** The important nodes along the coast include the Orange, Olifants and Berg Rivers and various groundwater areas. West Coast effects of freshwater inflow are therefore inshore and localised.

Along this coastline it would seem reasonable to assess the contributions of the various estuaries individually as the individual influence of an estuary is unlikely to be of sufficient spatial extent to overlap with that of an adjacent estuary. However, the recreational and commercial fisheries (inshore fisheries) are dependent on these 'pockets' of fish (*e.g.* gill net, beach seine fisheries targeting harders, West Coast Steenbras, Angolan Cob, *etc.*) occurring in the vicinity of estuary mouths.

In upwelling regions (West Coast), where dissolved nutrients are generally in adequate supply, other issues such as the role of freshwater plume dynamics (*e.g.* increased water column stability) in creating a favourable environment for increased water column productivity, and sediment and particulate organic matter discharges into the nearshore environment, are likely to be of greater importance. Factors resulting in enhanced nearshore habitats include turbidity and temperature.

It has been suggested that the West Coast estuaries may play a significant role in supplying detrital material to nearshore habitats in the vicinity of estuary mouths (*e.g.* Orange River, Berg River, *etc*)

Although changes in dissolved oxygen are not a significant driver in terms of freshwater inflow, it has been observed that fish use estuaries in this region as a refuge from low oxygen conditions, *e.g.* the Berg River seemed to provide a refuge for fish during the low oxygen event of 1994 (*pers comm.*, Lamberth).

Ecological response to submarine groundwater discharges

In the cool temperate region the submarine groundwater discharge ranges from discrete discharge between Cape Agulhas and Cape Point (winter recharge), predominantly diffuse surficial groundwater discharges through unconsolidated sediments between Cape Point and the region just north of St Helena Bay (also winter recharge) to predominantly alluvial groundwater discharges at mouths of ephemeral river systems in the region north of St Helena Bay.

On the West Coast seasonal changes in run-off are large, the run-off being mostly episodic. In such an environment submarine groundwater discharges may play a significant role in maintaining nutrient fluxes into the (nearshore) marine environment, however the submarine groundwater discharge in this region from basement type discharges are expected to be relatively limited and may also be quite variable over time. However, significant groundwater flows may occur at alluvial groundwater discharges. Locations where submarine groundwater discharge may be significant are at Varkenvlei (characterised by a high fish diversity), at the Groen and Spoeg Rivers (region encompassing the newly proclaimed Namaqualand Marine Protected Area), Donkensbaai and Holgat (*pers. comm.*, Steve Lamberth). Discrete submarine groundwater discharge is known to exist in the vicinity of the number of abalone farms located in the vicinity of Hermanus (Carter, *pers. comm.*)

During the low rainfall summer period there is significant upwelling along the West Coast suggesting that the role played by submarine groundwater discharge is likely to be limited. During the winter rainfall season, submarine groundwater discharges are likely to be greatest when freshwater inflows from rivers and estuaries also are the greatest, suggesting a limited role for submarine groundwater discharges. However it should be noted that estuarine and river discharges on the West Coast are few and far between. Thus the role of submarine groundwater discharges along the West Coast is considered to be limited (compared to the large nutrient fluxes due to upwelling) and, where potentially significant, the effect is expected to be localised. The import of SiO_2 via submarine groundwater discharge may be important in this region at times of diatom blooms when Si requirements are maximal and may not be met by SiO_2 concentrations in the water column.

It has been suggested that the West Coast estuaries may play a significant role in supplying detrital material to nearshore habitats. Submarine groundwater discharges into estuaries indirectly may play a role in determining the detrital material being discharges from estuaries.

7.3.2 *Socio-economic (resource utilisation) impacts*

The following potential socio-economic impacts associated with reduced freshwater inflows to the marine environment, were identified:

- changes in the recreational and commercial line fishery (e.g. gill net, beach seine fisheries targeting harders, West Coast Steenbras, Angolan Cob, *etc.*) occurring in the inshore region in the vicinity of estuary mouths;

- changes in the artisanal and subsistence fisheries, including filter-feeders.

8. Summary and Conclusions

The relationships between freshwater-derived fluxes into the marine environment and ecosystem response in the various regions are summarised below.

8.1 Summary

8.1.1 Subtropical region

The KwaZulu-Natal coastline between Durban and Richards Bay (*i.e.* the Natal Bight) operates as one large ecosystem. Conditions north of St Lucia and south of Durban are somewhat different in that the Agulhas Current influence is strong close inshore. The retention mechanisms that play a significant role in making the Natal Bight an important spawning and nursery area, in these regions are limited to small areas of re-circulation mostly in the nearshore region.

The freshwater inputs to the KwaZulu-Natal coast comprise inflows from many both small and larger estuaries. No one estuary, with perhaps the exception of the Thukela River, is likely on its own to have a substantial influence on the marine environment.

Along the KwaZulu-Natal coast the waters are largely oligotrophic, consequently the nutrient supply associated with the freshwater inflows are expected to be of greater relative importance. The relative importance of terrestrial and oceanic nutrient sources in nearshore and offshore ecosystems has not yet been determined, although there has been some progress in doing so. There is a strong correlation between river flow and fish egg abundance, *i.e.* there is evidence of increased spawning intensity during years of increased freshwater inflow to the marine environment. Presumably this also will result in conditions for enhanced survivability of fish larvae.

The supply of sediments is reported to be of significance in meeting the habitat requirements of important fisheries species (*e.g.* prawns), particularly over the Natal Bight. However, most of the sediments discharged onto the shelf are considered to be exported from the shelf into deeper waters, the only major accumulations occurring in relatively quiescent areas or areas of re-circulation (*e.g.* off the Thukela River and off St Lucia). Evidence that increased fine sediments over the shelf would favour flatfish species in this region is provided by the observed increase in the abundance of flatfish after the massive inflow of sediments to the shelf region that occurred during the 1987 floods.

Detailed studies undertaken as part of the Thukela RDM study (Louw, 2003) indicate that there is a strong relationship between prawn catch and an environmental index comprising a linear combination of a ***nursery index*** and a ***nutrient index*** (see Part I: Section 2.2). The overall

environmental index developed explained 77% of the variance of the prawn catch data. Although the study indicated a clear and strong relationship between freshwater inflows to the marine environment, only a relatively insignificant change in the prawn fishery was predicted for the development scenarios proposed for the Thukela River.

Similarly, a significant relationship exists between flow and catch for both commercial and recreational line fisheries. There is a correlation between flow and catch on short time scales (indicating behavioral responses to freshwater inflows), on intermediate time scales of approximately 4 months (indicating increased larval fish survival, greater food availability, *etc*) and on longer time scales approximating the time to first capture (indicating a response to wet and dry cycles, the catch being greater during wet cycles).

During this investigation, no studies were found that specifically address the role of submarine groundwater discharges in coastal ecosystems of the Subtropical coastal region.

8.1.2 Warm temperature region

Along the South Coast, from Cape Point to Algoa Bay, the coastline comprises a number of large bays separated by sweeping beaches and prominent headlands. The Agulhas Current lies far offshore while the flows over the adjacent shelf are largely wind-driven despite the strong influence of the Agulhas Current. Here the ecosystems function largely on a coastal embayment scale, however the ecosystems further offshore are more spatially extensive. The influence of freshwater flows is likely to be limited in this offshore zone, except for perhaps sediment inputs.

Japp *et al.*, (1994) suggests that estuaries are not important to the life histories of most fishes of the Agulhas Bank, however Lamberth and Turpie (2003) indicate that the economic values of the estuarine contribution to the fisheries in this region is significant.

The existence of certain river-derived substrates are associated with the spawning behaviour of fishes in this region, *e.g.* off the southeast Cape coast white steenbras *Lithognanthus lithognanthus* is known to spawn in July - August in the vicinity of mud banks deposited by rivers in this region (Bennet, 1993).

Inshore areas are important nurseries for juveniles of large predatory fish, as well as some small species that feed mainly on small crustaceans such as mysids that are particularly important dietary items of smaller members of the nearshore fish community. Surf zones are hypothesised to provide ideal interim nursery areas for recruitment sized larval fish of estuarine-dependant fish species. If correct, it may be important to maintain freshwater inflows to estuaries and consequently to the nearshore environment not only to ensure "connectivity" of estuaries via this "cueing corridor" but also to ensure optimal surf-zone habitats (*e.g.* in terms of nutrients, phytoplankton production, zooplankton, *etc*). Associated with the estuarine nursery function is the role of possible cueing effects. These have been studied in fair detail along this coastline,

providing convincing evidence for such a cueing effect, however the exact nature of the cueing signal remains uncertain.

The effect of potential impacts of changes in sediment discharges to the marine environment on shoreline erosion and accretion is largely unknown. Studies, where they exist, are likely to be focussed on only localised consequences.

Studies in Algoa Bay indicate, where they occur, that direct groundwater discharges into the marine environment play a significant role in the nearshore ecology, *e.g.* submarine groundwater discharges are a significant source of nitrogen to the surf diatom *Anaulus australis* that is an important source of food to animals living in the surf-zone such as mysid shrimps and the penaeid prawn that , in turn, are important dietary items of smaller members of the nearshore fish community (Campbell and Bate, 1998). The effects of groundwater, although often constrained spatially, may therefore be locally important, as observed in Algoa Bay. Similarly, groundwater flows may promote the growth of benthic diatoms and algal growth of sufficient spatial extent to play a significant role in early life cycles of fish larvae.

In general the potential role of cueing effects by groundwater is unknown, but could be significant at closed estuary mouths and mouths of ephemeral river systems. However Strydom and d'Hotman (2005) did not observe any accumulatory response of fish larvae at low salinity sites due to groundwater seepage along the shoreline in eastern Algoa Bay. They suggested that this lack of response was due to the catchment odours, necessary to drive this process, being lost in the passage of the freshwater through the sand.

The accuracy of the above observations needs to be confirmed. In particular, potential submarine groundwater discharges need to be better characterised and a dedicated effort to identify groundwater-dependant marine ecosystems is required (see Section 5.4 above)

8.1.3 Cool Temperate Region

On the West Coast, there are a more limited number of rivers and estuaries that also are relatively remote from one another suggesting that the individual influence of an estuary is unlikely to be of sufficient spatial extent to overlap with that of an adjacent estuary. However, the recreational and commercial fisheries (inshore fisheries) are dependent on these 'pockets' of fish (*e.g.* gill net, beach seine fisheries targeting harders, West Coast Steenbras, Angolan Cob, *etc.*) occurring in the vicinity of estuary mouths.

In upwelling regions (West Coast), where dissolved nutrients are generally in adequate supply, other issues such as the role of freshwater plume dynamics (*e.g.* increased water column stability) in creating a favourable environment for increased water column productivity, and sediment and particulate organic matter discharges into the nearshore environment are likely to be of greater importance. Factors resulting in enhanced nearshore habitats include turbidity and temperature. It is possible that estuaries in the West Coast region may provide an important source of POM to

nearshore fish communities in the vicinity of estuary mouths (*e.g.* Orange River, Berg River, *etc.*) Some of the estuaries in the region also may provide important refuge areas during low oxygen conditions.

Although submarine groundwater discharges may provide a source of nutrients to nearshore habitats, there is no evidence to date indicating that submarine groundwater discharges play a significant role in such a high nutrient upwelling region as the West Coast.

8.2 Conclusions

From the above summary we conclude that:

- There is **adequate evidence that freshwater inflows to the marine environment affect marine ecosystems to a greater or lesser degree along the whole South African coastline**. The magnitude of these effects decrease on moving from the East Coast where the coastal waters are largely oligotrophic to the West Coast dominated by the upwelling of nutrient-rich seawater. It has been demonstrated that freshwater inflows significantly affect the commercial and recreational line fishery and the prawn fishery off KwaZulu-Natal, as well as spawning intensity along the KwaZulu-Natal coastline. Along the southeast, southern and West Cape coastline there are demonstrable effects on fish in the inshore habitats. The effect of submarine groundwater discharges is uncertain and needs to be further clarified.
- The **nature of the interaction between terrestrial and marine environments differs substantially in the various regions, suggesting that region-specific approaches are required** in assessing the freshwater requirements of the marine environment. It is proposed that:
  - the KwaZulu-Natal Coast behaves as one large ecosystem and should be assessed regionally;
  - the Eastern Cape Coast, extending from the Kei River to just of Port Edward and comprising a more rocky coastline with numerous small, sandy pocket beaches and many small estuaries that is exposed to the Agulhas Current, is best assessed using a more nodal approach;
  - the South Coast, from Cape Point to Algoa Bay be assessed on a coastal embayment scale, however the ecosystems further offshore are considered to be more spatially extensive;
  - the West Coast with its more limited number of rivers and estuaries that are relatively remote from one another requires that the assessment be undertaken on a node by node basis;
- While there are some studies indicating a strong interaction between terrestrial and marine environments, particularly on the East Coast, the exact nature and significance of these **relationships between freshwater-derived fluxes into the marine environment and ecosystem response both in the marine environment is relatively poorly**

understood. It is recommended that further research be undertaken as detailed in the Section 9 below.

9. Recommendations

The recommendations that follow are based on both higher level considerations associated with appropriate assessment frameworks and methods as well as more basic research into the relationships between freshwater-related changes in abiotic (and biotic) drivers and ecosystem response.

9.1 Assessment Frameworks and Methods

An assessment and management framework, that takes cognisance of the freshwater requirements of the marine environment, needs:

- ***to have clearly defined and agreed upon goals and environmental objectives.***
- ***to resolve the issues of jurisdictional fragmentation and deficiencies in legislation***
- ***to provide sufficiently robust and quantitative assessments of the importance of freshwater inflows to marine systems so as to effectively motivate, where necessary, for an ecological reserve for the marine environment.*** In particular, the assessment methods need to provide a ***clear analysis and management of uncertainty in the assessment and management framework*** for managing the marine environment in terms of its freshwater requirements.
- ***to be simple and inexpensive yet sufficiently robust and quantitative to provide the necessary management advice, i.e. the methods used need to deal adequately with the complexity of the ecosystems*** being assessed but within ***the limited time and resources typically available*** to make such assessments.

Given the uncertainty in predicting the ecological effects of water management strategies/activities or the efficacy of measures aimed at regulating them, suggests the need for an active or adaptive rather than a passive management strategy.

An existing initiative that meets these requirements is the ECO^3 concept presently being developed under the leadership of the CSIR (Peters *et al.*, 2007). It is an initiative that intends to provide a robust and flexible framework for providing a holistic assessment of ecosystem and economic (and social) imperatives when considering potential future developments that will either indirectly or directly affect the exploitation of natural resources. This methodology is well-suited to the informing the allocation of freshwater resources between catchments, estuaries and the marine environment, provided that the basic ecosystem responses are sufficiently understood.

A technique well-suited to assessing the complex ecosystems existing at the terrestrial-estuarine-marine interface is that of Bayesian networks. Not only do these networks deal well with complexity, they also are capable of handling data of highly disparate detail and uncertainty. In addition, uncertainty is explicitly handled in Bayesian networks.

It is recommended that the ECO^3 concept be pursued and that techniques such as Bayesian networks be used to better quantify the relationships between freshwater-related changes in abiotic (and biotic) drivers and ecosystem response in the marine environment of South Africa. Ultimately a sufficient understanding of the ecosystem functioning sufficiently needs to be developed to be able to make recommendations on probable allowable changes in freshwater inflow into the marine environment within the constraint of maintaining or improving the present health status of the marine ecosystem under evaluation.

There is a relatively poor appreciation of the role of freshwater inflows to the marine environment. A better appreciation of the role of freshwater inflows to the marine environment on marine ecosystems can be achieved through:

- undertaking the basic research required to elucidate the effect of reductions in freshwater inflows to the marine environment on marine ecosystems and the associated potential socio-economic impacts;
- involving and developing young scientists through involvement in focussed research projects and field work;
- publishing the outcomes of this study and potential follow-up research.

It is anticipated that extending existing RDM protocols to include inputs to the marine environment from estuary and estuary processes will not be too onerous and costly and should be attempted as a matter of course when undertaking future RDM assessments.

9.2 Changes in freshwater inflow and ecosystem response

Specific issues that need to be resolved include:

- Identifying appropriate keystone or indicator species for the ecosystem(s) under consideration;
- Identifying appropriate trajectory of changes parameters;
- Deciding on the appropriate method of assessment for the various regions under consideration, *i.e.* do assessments need to be regional, nodal or undertaken on some other spatial scale?

- Deciding whether it is possible and how to parameterise short time scale responses using the limited longer term data that is typically available (*e.g.* can one reasonably derive estimates of daily flow given only weekly or monthly flow averages?);
- Do data or model predictions/hindcasts exist that will enable one to assess changes in freshwater discharges over last 50 years and anticipated changes over next 50 years?
- Have reductions in freshwater inflow to the marine environment resulted in reduced nutrient and sediments fluxes to the marine environment or have anthropogenic influences such as changes in catchment usage, effluent discharges to estuaries, etc. resulted in increased nutrient and sediment fluxes to the marine environment? In particular, the assumption that reductions in freshwater flows, particularly floods and freshets, significantly change the quantity of sediments discharged into the marine environments needs to be tested.
- What are the changes in freshwater flows scenarios predicted for the future?

Specific recommendations for future research are that:

- **Existing freshwater inflows and associated nutrient (inorganic nutrients and organic matter) and sediment fluxes to the marine environment need to be robustly estimated.** A suggested approach is that adopted by WL | delft hydraulics and IFREMER (WL| delft hydraulics, 2003). The approach they use is to classify estuaries in terms of "indicators" that play a role in determining the potential nutrient and sediment inputs into the marine environment from a particular estuary. Similar classifications have been undertaken for South African estuaries both in a more generic sense (Whitfield, 1992) and more specifically in terms of biodiversity attributes (Turpie *et al.*, 2004). By focussing on the classification of estuaries into classes based on indicators having a strong influence on mouth condition, nutrient and sediment inputs by estuaries into the marine environment, it is intended to develop of a generic estuary model (GEM) for a particular "class" of estuary that would allow one to estimate mouth condition, nutrients and sediment fluxes for one estuary in such a class (for which there is adequate data) and extend these estimates to other similar estuaries in that class, based on a simple measures such as flow. In so doing, is hoped to obtain estimates of mouth condition and nutrient and sediment fluxes for all estuaries in a particular class. If this can be achieved for all of the estuary classes identified for a particular region then it will be possible to proceed with the integrated hydrodynamic and/or water quality modelling required to support an assessment of the influence of freshwater inflows (and associated nutrient and sediment fluxes) into the marine ecosystem of interest. (Such an assessment would also consider the impact on mouth conditions and estuarine health on the nursery function supplied by estuaries.) However, it is not clear to what extent this approach could provide the information required to ensure an assessment that is sufficiently robust to be able to recommend the freshwater requirements of a particular marine ecosystem.

- **A regional assessment be undertaken of the KwaZulu-Natal region, specifically the Natal Bight:** This will require, amongst other measurements that a hydrodynamic and/or water quality model of the marine environment be set-up to simulate the transport, dispersion and ultimate fate of nutrients and sediments in the marine environment. Such a modelling study should characterise both spatially and temporally the various drivers determining the habitat suitability (*e.g.* extent and persistence of nutrients and sediments in the various habitats) in the marine environment. In particular, the modelling should be able to resolve the abiotic drivers that make the various habitat domains (estuarine, nearshore/surf-zone and shelf) distinct in terms of their ecological functioning. For example, more limited freshwater inflows (typically base flows from estuaries) to the marine environment are likely to result in nearshore habitats of relevance to fish species dependant of the existence of specific nearshore conditions for their survival and recruitment success. The extent of these nearshore habitats and the interconnectivity of estuarine habitats associated with these nearshore habitats are largely determined by the nature of the freshwater inflows, proximity of the estuaries to one another and the prevailing metocean conditions. Conversely, large freshwater inflows, *e.g.* floods, are likely to result in extensive low salinity, turbid plumes in the marine environment with their associated nutrient and sediment inputs leading to higher productivity in these offshore environments, but also physico-chemical conditions (*e.g.* fronts, *etc.*) leading to a significant ecological response in the marine environment. The modelling, in particular, needs to address:

  - the extent and persistence of the various nearshore and surf-zone habitats and the extent of interconnectivity between the various estuarine environments along a particular stretch of coastline.
  - the extent and persistence of the low, salinity turbid plumes in the marine environment and ultimately the nutrient loads (and their subsequent utilization) and the sediment loads (and their ultimate transport and fate) in the marine environment.

  The requirements of such a modelling study are detailed in van Ballegooyen and Gulekana (2005). Ultimately numerical model simulations also should be undertaken in support of research in other regions such as the south-eastern Cape where, for example, a greater understanding of surf-zone dynamics is required.

In addition to the above research initiative, it is recommended that:

- the existing research effort off KwaZulu-Natal to determine the relative importance of terrestrial and oceanic nutrient sources in nearshore and offshore ecosystems between wet and dry years be both supported and expanded so that the stable isotope analyses undertaken for "normal" years can be extended to include "wet" years. The use of stable isotope analyses should be expanded to gain a better idea of the relative importance of terrestrial and marine sources of nutrients/detritus in food webs and food web structure;

- the observed strong correlation between river flow and fish egg abundance off KwaZulu-Natal be further investigated and an effort made to publish these results;
- a better understanding is obtained of the sediment dynamics of both the nearshore and deeper waters, particularly over the Natal Bight where it is reported that most sediment do not remain on the shelf unless deposited during floods or entrained in circulations that result in relatively quiescent region on the shelf;
- a better understanding be obtained of phytoplankton and sediment (including POM) dynamics over the Natal Bight using ocean colour remote sensing;
- it be determined how many of the nursery areas indeed perform a significant nursery function (particularly in a regional sense). This is important as it informs risks involved in "losing" one of more estuaries performing a nursery function;
- the cueing effect be further investigated to determine its nature (*i.e.* is it olfactory or not?) and importance for recruitment into estuaries;
- the concept of the surf-zone as a "cueing corridor" and the interconnectivity of estuaries due to surf-zone dynamics be further investigated;
- the potential localised inshore influence of river inputs on the West Coast (commercial gill net and beach seine fisheries) be assessed;
- given that the impact of submarine groundwater discharges is unknown, it is proposed that the methods of identifying potential submarine groundwater discharges be reviewed and an attempt be made to identify and map possible submarine groundwater discharges along the South African coastline. This exercise should be accompanied by an effort to confirm the mapping of submarine groundwater discharges. This is likely to include field surveys that attempt to identify locations of groundwater-dependant ecosystems. A study, complementary to the effort to map potential submarine groundwater discharges is proposed whereby groundwater quality data for coastal sites is utilised to estimate potential nutrient loads into the marine environment. Based on these estimated nutrient loads, the potential importance of these submarine groundwater discharges to the nutrient budgets of marine ecosystems need to be quantified, particularly those into the surf-zone. This implies that the nutrient budgets for the marine ecosystems of the various biogeographic domains need to be adequately quantified (*i.e.* there is a need to understand the nutrient inputs to a particular region, whether from offshore, river/estuaries or submarine groundwater discharges). The relevance of the submarine groundwater discharge as a major source of nutrients to these ecosystems depends on a complementary effort being undertaken to estimate the nutrient inputs to these ecosystems from rivers and estuaries as well as from deeper waters. The extent to which it is possible to quantify the ratio of river to submarine groundwater discharges nutrients entering the marine environment, needs to be determined;

- an effort be made to publish as yet unpublished research into coastal processes in inshore/nearshore environments and that further multi-disciplinary studies undertaken in these inshore/nearshore environments to assess the effects of changes in freshwater flows to the marine environment;
- the effect on South African marine ecosystems of potential changes in freshwater flow from catchments and in metocean conditions associated with climate change, be assessed.

Important to all of the above investigations/assessments is that simultaneous data model outputs be acquired for all drivers and ecosystem components forming part of the assessments.

Given the scope of work required, it is important that partnerships be created between both national and international research groups. In particular a partnership with Marine and Coastal Management and DEAT is important as they have the legislative mandate for the affected environment and resources.

9.3 National and International Research Programmes

National and International programmes that potentially could contribute to research into the freshwater requirements of the marine environment include:

- Land-Ocean Interactions in the Coastal Zone (LOICZ)
- Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA)
- African Coelacanth Ecosystem Programme (ACEP)
- Agulhas-Somali Large Marine Ecosystem (ASLME)
- EU-funded projects.
- Coastal GOOS/AfriGoos
- BENEFIT Project: (Orange-Kunene studies)
- ACCESS (Africa Centre for Climate and Earth System Science) initiatives
- SEAWATCH programme
- MCM, ORI and CSIR research programmes
- Universities – typically short-term intensive data sets used for MSc or PhD
- Large coastal municipalities - shoreline data collecting, water quality data and sediment data
- Coast Care.

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APPENDIX A:
National Legislation

This appendix provides a brief overview national legislation of relevance when developing an appropriately comprehensive and robust assessment and management framework for the coastal and offshore marine environment that takes cognisance of their freshwater requirements.

A1 Constitution of South Africa

The Constitution of South Africa (Act 108 of 1996), in particular the Environmental Right (section 24), states that:

"Everyone has the right

b. to an environment that is not harmful to their health or well-being; and

c. to have the environment protected, for the benefit of present and future generations through reasonable legislative and other measures that –

i. prevent pollution and ecological degradation;

ii. promote conservation; and

iii. *secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development'.*

This section of the Bill of Rights guarantees the people of South Africa the right to an environment not detrimental to human health or well-being, and specifically imposes a duty on the State to promulgate legislation and take other steps to ensure that the right is upheld and that, among other things, pollution and ecological degradation is prevented.

A2 National Environmental Management Act 107 of 1998 (NEMA)

Chapter 1, Section 2 of NEMA states the broad principles that must be considered in setting objectives for the environment and appoints national DEAT as the lead agent responsible for the implementation of NEMA. Furthermore, these principals serve as the general framework within which environmental management and implementation plans must be formulated.

Section 2 (4) states that sensitive, vulnerable, highly dynamic or stressed ecosystems, such as coastal shores, estuaries, wetlands and similar systems require specific attention in management and planning procedures, especially where they are subjected to significant resource usage and development pressure.

A3 National Water Act 36 of 1998

Chapter 3 of the Water Act sets out legal mechanisms to protect water resources. The Resource Directed Measures (RDMs) include Classification and setting Resource Quality Objectives (RQOs) as well as the determination of the Reserve. Chapter 3 of the Water Act also describes Source Directed Controls (SDCs) which aim to minimise the impact of certain polluting activities.

Resource Quality Objectives (RQOs) also need to be defined for the water resource (i.e. physical dynamics, water quality, biota and habitat) in a measurable format. The Water Act defines *Resource Quality* (Section 13) as the quality of all the aspects of a water resource including:

- Quantity, pattern, timing, water level and assurance of instream flow;
- Water quality, including the physical, chemical and biological characteristics of the water;
- Character and condition of the resource habitat; and
- Characteristics, condition and distribution of the aquatic biota.

A significant omission of the national Water Act is that it **does not define the marine environment as a water resource**. As a result, the protection given to water resources such as estuaries does not apply to marine waters. The act does however provide a generic approach and a set of measures that, to a large extent, are likely to be appropriate for the marine environment.

A4 Marine Living Resources Act 18 of 1998

The national Department of Environmental Affairs and Tourism is, in terms of the Marine Living Resources Act, the lead agency for the management of the living resources of marine environment. Section 2 of the act states that the Minister and any organ of state with the relevant authority, shall have regard to the following objectives and principles:

- optimum utilisation and ecologically sustainable development of marine living resources;
- conservation of marine living resources for both present and future generations;
- applying a precautionary approach in respect of the management and development of marine living resources;
- utilising marine living resources to achieve economic growth, human resource development, capacity building within fisheries and mariculture and employment creation;
- protection of the ecosystem as a whole, including species which are not targeted for exploitation;
- preservation of marine biodiversity;
- broad and accountable participation in the decision-making processes;
- obligation of the national government in terms of any international agreement or international law.

A5 National Environmental Management: Integrated Coastal Management Bill

Section 23 of the Integrated Coastal Management Bill proposes that the Minister (DEAT) or Provincial MEC be given the responsibility to declare special management areas by notice in the *Government* or *Provincial Gazette,* should environmental or socio-economic conditions in that particular area require the introduction of special measures in order to: attain the objectives of a coastal management programme; more effectively facilitate the management of coastal resources by local communities; promote sustainable livelihoods for local communities and conserve, protect or enhance coastal ecosystems of biodiversity in the area.

Sections 41 and 42 state that the Minister (DEAT) is responsible for preparing and adopting a National Coastal Management Programme for managing the coastal zone, including a national vision and national coastal objectives and the priorities and strategies to achieve this.

Sections 44 and 45 propose that the Provincial MEC's are responsible for preparing and adopting Provincial Coastal Management Programmes for managing the coastal zone in the four coastal provinces, including a vision for each province and coastal management objectives, as well as the priorities and strategies to achieve this, in alignment with the National Coastal Management Programme.

A6 Environmental Conservation Act 73 of 1989

Although many of the provisions of the Environmental Conservation Act have been repealed by the National Environmental Management Act, the Environmental Impact Assessment (EIA) regulations (implementing sections 21, 22 and 26 of the Act), as well as the regulation on Sensitive Coastal Areas remain in force until they are replaced with new regulations under the National Environmental Management Act. Under the EIA regulations, certain activities require an impact assessment prior to approval.

A7 National Environmental Legislation: Biodiversity Bill

Although still in draft form, this Bill's focus is to protect biodiversity and will also be administered by the DEAT.

- Section 39 states that the national biodiversity framework must provide for an integrated, co-ordinated and uniform approach to biodiversity management, be consistent with the NEMA principals, identify priority areas for conservation action and the establishment of protected areas and reflect regional co-operation on issues concerning biodiversity management in Southern Africa. The national biodiversity framework may determine norms and standards for provincial and municipal environmental conservation plans.

- Section 41 states that a bioregional conservation plan must contain measures for the effective management of biodiversity and the components of biodiversity in the region. Section 41 proposes that the national biodiversity framework must set performance indicators against which progress with the achievement of strategic objectives could be measured as well as to set up mechanisms to monitor and measure such progress.

- Section 46 proposes that the Minister of the Department of Environmental Affairs and Tourism review biodiversity conservation plans (that identify the components of biodiversity that are important for biodiversity conservation and the sustainable use of biological resources or which are inadequately conserved or understood) at least every 5 years. Monitoring mechanisms need to be established for such components (Section 49). Indicators also need to be set to determine the conservation status of the components and any negative and positive trends affecting the conservation status of the components.

A8 National Environmental Management: Protected Areas Bill

Although still in draft form, this Bill deals with the establishment, management and control of protected areas with the Department of Environmental Affairs and Tourism as the responsible authority. Sections of relevance here include:

- Section 9 proposes the following system of protected areas in South Africa:
  - special nature reserves, national parks, nature reserves and protected environments;
  - world heritage sites;
  - marine protected areas;
  - specially protected forest areas, forest nature reserves and forest wilderness areas declared in terms of the National Forests Act (84 of 1998); and
  - mountain catchment areas declared in terms of the Mountain Catchment Areas Act (63 of 1970).

- Section 14 states that most of the provisions in the bill do not apply to marine protected areas (except for Chapter 1, this Chapter and Section 48), but if a marine protected area has been included in a special nature reserve, national park or nature reserve, such area must be managed and regulated as part of the special nature reserve, national park or nature reserve.

- Section 17 of the Protected Areas Bill states that the purpose of protected areas is:
  - to protect ecologically viable areas representative of South Africa's biological diversity and its natural landscapes and seascapes in a system of protected areas;
  - to preserve the ecological integrity of those areas;
  - to conserve biodiversity in those areas;

- to protect areas representative of all ecosystems, habitats and species naturally occurring in South Africa;
- to protect South Africa's threatened or rare species;
- to protect an area which is vulnerable or ecologically sensitive;
- to assist in ensuring the sustained supply of environmental goods and services;
- to provide for the sustainable use of natural and biological resources;
- to create or augment destinations for nature-based tourism;
- to manage the interrelationship between natural environmental biodiversity, human settlement and economic development;
- generally, to contribute to human, social, cultural, spiritual and economic development; or
- to rehabilitate and restore degraded ecosystems and promote the recovery of endangered and vulnerable species.

Most of the above Bills are available at http://www.capegateway.gov.za.

APPENDIX B:
Schematic of relationships between the various abiotic and biotic drivers and the ecosystem response

B.1 Life cycles of shorter-lived species

The preliminary schematised pathways of factors influencing the prawn (shrimp) life cycle in Maputo Bay as reported for the Catchment2Coast project (INCO, 2003) indicates the potential complexity and nature of the type of analysis required for shorter-lived keystone or indicator species used to assess of the potential freshwater requirements of the coastal and offshore marine environment of South Africa..

Clearly it will be very difficult to quantify and determine their relative importance and effects of the population dynamics. The utility of Bayesian networks in helping to do so has been well-documented (*e.g.* Borsak *et al.*, 2004; Baran *et al*, 2004 and de Waal, 2004).

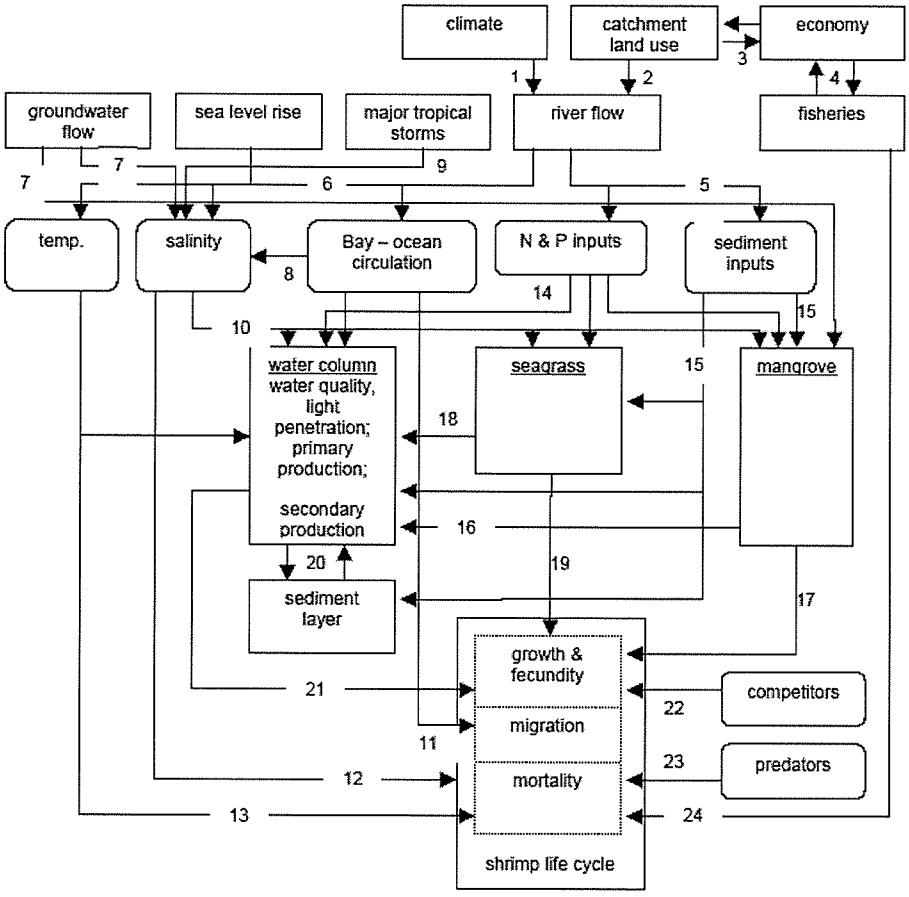


Figure B.1 Schematised pathways of factors influencing the habitat requirements of the prawn (shrimp) life cycle, Maputo Bay (after INCO, 2003)

Key to figure Figure B.1 above:

1. *Climate* (change): exerts an influence on river flow through precipitation and evaporation rates.
2. *Catchment landuse*: influences through run-off the water volumes and nutrients that enter the river.
3. *Economy – land use*: complex interactions (long term).
4. *Economy – fisheries*: market prices influence fisheries effort and vice versa (short term).
5. *River flow / water quality*: provides an input to the bay of suspended sediments and nutrients.
6. *River flow / water quantities*: influences the salinity of the Bay waters as well as its temperature (estuary/Bay/coastal waters scale).
7. *Groundwater flow*: influences the salinity of mangrove soils and adjacent waters (local effect)
8. *Bay-ocean circulation*: influences the salinity gradients in the Bay
9. *Rainfall from tropical storms*: can have a possible significant effect on local salinity.
10. *Salinity*: influences the water column processes and the growth of seagrass and mangroves.
11. *Shrimp migration pattern*: influenced by Bay-ocean circulation patterns
12. *Salinity*: influences the physiology of the shrimp (could also have an effect on the transformation from one larval stage to another).
13. *Temperature*: influences the physiology of the shrimp
14. Nutrient input: influences the water column processes, growth of seagrass and mangroves.
15. Sediment input: influences the growth of seagrass and mangrove and plays a role in the water column through light penetration and water sediment composition.
16. Mangrove: is a source of organic matter (detritus) to the water and soil compartments.
17. Mangrove: provides a habitat and food for juvenile shrimp (esp. *P. indicus*).
18. Seagrass: influences the water column and sediment layer in a variety of ways (source of detritus, oxygen, sedimentation of suspended matter etc.)
19. Seagrass: provides a habitat and food for juvenile shrimp (not relevant for P. indicus?)
20. Sediment layer – water column interaction: exchange of matter.
21. Water column: primary and secondary production provides food for juvenile and adult shrimp.
22. Competitors: compete for food with juvenile and adult shrimp.
23. Predators: factor of (unknown) mortality rate of shrimp (all stages)
24. Fisheries: factor of mortality rate of adult shrimp.

B.2 Life cycle of longer-lived species.

The schematic in Figure B.1 was developed around the life-cycle of estuarine dependant fish species, however it is sufficiently generic to explain most of the interrelationships between abiotic and biotic driver as well as the potential ecosystem response where there is an estuarine or freshwater dependence. The fluxes between the water-sediment interface in the marine environment is not explicitly included in the schematic, however it is recognised that these are important and would need to be included where relevant.

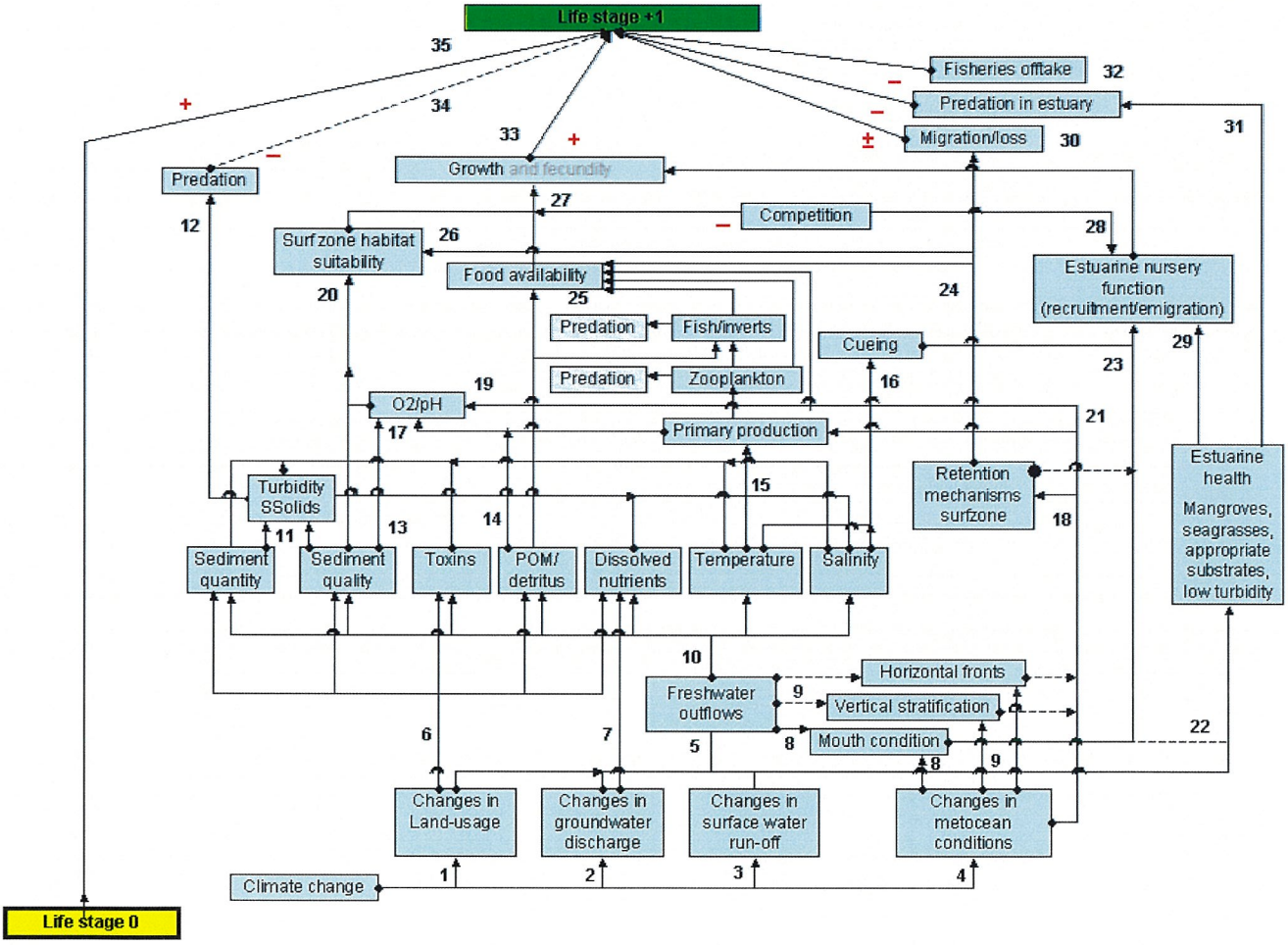


Figure B.2: Idealised interrelationships between the various abiotic and biotic components affecting ecosystem response, particularly insofar as they are related to changes in freshwater inflows to the marine environment.

The key to Figure B.2 is given below:

1. Climate change is expected to have a significant impact in land-usage in the catchment
2. Climate change is expected to have a significant impact on groundwater fluxes both due to changes in groundwater recharge and groundwater utilisation.
3. Climate change is expected to have a significant impact on surface water fluxes both due to natural changes in run-off and as well as utilisation of water resources.
4. Climate change is expected to impact upon metocean conditions, *e.g.* changes in storminess, long-term rise in sea levels, *etc.*
5. Changes in land usage, groundwater discharges and surface water run-off all affect the freshwater related inflows to the marine environment
6. Land usage directly affects the inflow of sediments quantity and quality, toxins, nutrients (dissolved and POM) to the marine environment. Changes in land-use may increase or decrease the availability and size distribution of sediments entering the marine environment. Similarly, land-use may change the POM and concentration of dissolved nutrients and toxins available for discharge into the marine environment. The loads of sediments, nutrients and toxins entering the marine environment is a combination of availability as well as the flow rates associated with groundwater discharge and surface water run-off (see bullet 10).
7. Nutrient concentrations in groundwater may be high. Consequently groundwater may be a significant source of dissolved nutrients to the marine environment both through direct discharge into coastal waters or indirectly through discharge into river and estuarine environments.
8. The mouth condition (*i.e.* the extent to which the mouth of an estuary is open or closed) is predominantly determined by a) the freshwater outflows from estuaries and b) metocean conditions (including sediment availability).
9. Freshwater outflows to the marine environment effect both horizontal and vertical fronts in the adjacent coastal and marine environments, the extent of the fronts and vertical stratification increasing with increasing freshwater-related outflows to the marine environment. The extent and persistence of these horizontal and vertical fronts is also significantly influenced by prevailing metocean conditions in the vicinity of the freshwater inflow.
10. Freshwater and freshwater-related outflows to the marine environment affect the sediment quantity and quality, toxin loads, nutrients loads (POM and dissolved) and temperature and salinity in the marine environment.
11. The sediment quality (grain size distribution) and quantity discharged to the marine environment, together with the rate of discharge will determine the turbidity of the surrounding coastal and offshore marine environment. Once these sediments are in the marine environment, the extent and persistence of turbid conditions will also be significantly influenced by metocean conditions, particularly waves.
12. The turbidity of the water affects predation due to the requirement for predators on seeing their prey. Turbid waters therefore afford protection to their prey. However, in terms of fishery offtake, fishers often target turbid waters due to the aggregation of their target specie(s) in such waters.
13. Sediment quality has the potential to impact upon dissolved oxygen in the sediments and the water column
14. POM and detritus has the potential to impact upon dissolved oxygen in the sediments and the water column.
15. Temperature, salinity, dissolved nutrients (food), turbidity (light) and toxins all are expected to influence phytoplankton production in the marine environment.
16. The exact nature and physiological basis of this cueing effect is not yet understood, although evidence exists that it may be olfactory in nature. The chances are that salinity and/or temperature distributions would provide some measure of the extent of cueing effects.
17. Primary production and sediment quality have the potential to impact upon dissolved oxygen in the sediments and the water column.

18. The extent and persistence of vertical and horizontal fronts and metocean conditions all determine the extent to which retention mechanisms play a role in maintaining biota in suitable habitats. For example, wave conditions and wave-driven currents determine the extent to which fish larvae are retained within the surf-zone.

19.. The extent and persistence of vertical and horizontal fronts and metocean conditions all regulate to a greater or lesser extent the turbulent mixing in the marine environment that, in turn, plays a role in determining the extent of vertical fluxes of dissolved oxygen and other water quality parameters.

20. Sediment quantity (physical habitat), sediment quality, the presence of toxins, temperature and salinity all determine habitat suitability in the marine environment whether in the surf-zone or further offshore.

22. The extent and persistence of vertical and horizontal fronts and metocean conditions all are factors governing levels of primary production in the marine environment (*e.g.* by retaining phytoplankton in optimal light conditions, *etc.*).

23. Land usage, surface water and groundwater abstraction and mouth conditions in an estuary all play a major role in determining estuarine health and whether habitat forming species (mangroves, seagrass, *etc.*) are present and thrive in an estuary.

24. The cueing effect and open mouth conditions are both necessary factors ensuring that there is recruitment to the estuaries while open mouth conditions are required for subsequent emigration from the estuaries.

25. Food availability is determined both by the actual availability of food in a particular environment and the ability of biota to remain in the environment where there is food, i.e. there is a dependency on retention mechanisms particularly amongst the early life stages.

26. While factors such as sediment quantity (physical habitat), sediment quality, the presence of toxins, temperature and salinity all determine habitat suitability, there is also a requirement for the biota to remain within the desired habitat. For particularly the early life stages, retention mechanisms play a role in determining whether or not this occurs.

27&28. Competition for food and habitat will affect the growth of the target species both in the marine and estuarine environments.

29. Estuarine health largely will determine the extent to which a particular estuary fulfils an estuarine nursery function.

30. Migration losses will reduce the abundance of a particular species from the biogeographical domain under consideration.

31. Estuarine health, particularly the presence or absence of habitat forming species such as mangroves and seagrasses will impact upon predation levels in the estuary.

32. If the species under consideration forms part of a fishery, there will be a fisheries offtake resulting in a reduction in abundance and biomass.

33. A reduction in growth (and fecundity) will obviously have a major impact on abundance and biomass of the species under consideration.

34. Predation by natural predators will reduce the abundance and biomass impact on abundance and biomass of the species under consideration.

35. A significant factor in determining abundance and biomass is the abundance and biomass of the preceding life stages.

APPENDIX C:
Learning from the initial workshop

The initial approach proposed to assess the freshwater requirements of the marine environment of South Africa was amended during the project in response to outcomes from the initial workshop being different to those originally anticipated.

C.1 Initial proposed approach and methods

The approach and methods proposed to meet the Scope of Work for this project was as follows:

- The CSIR would to develop a conceptual framework for assessing the freshwater requirements of the coastal and offshore marine environments intended to provide the basis for an initial workshop as described below.
- Based on this assessment framework the CSIR would hold an initial two day workshop attended by a wide range of estuarine, coastal and marine specialists having the necessary expertise to undertake a preliminary assessment on where the reduction of freshwater and sediment discharges to coastal and offshore marine environments is likely to have an impact on coastal and offshore ecosystems. The purpose of this initial workshop was to:
  - ***familiarise all participants of the workshop with the RDM process*** as it would be used as a starting point to assess the freshwater requirements of the marine environment,
  - collate ideas around the ***nature of the physico-chemical and ecological links between river/estuarine environments and the coastal/offshore environment in the various coastal/offshore domains surrounding southern Africa*** most likely to be impacted upon by changes in freshwater, nutrient and sediment inflows to the marine environment. This would be achieved by:
    - *identifying and characterising the potential changes in abiotic (and biotic) drivers of coastal and offshore marine ecosystems* due to a reduction freshwater inflow to the coastal and offshore marine environments,
    - *identifying (on a region by region basis) those components of coastal and offshore ecosystems most likely to be significantly impacted upon* by changes in freshwater and sediment inflows to these environments,
    - based on the concept of an abiotic (and biotic) driver - ecological response model, attempt to *describe how changes in abiotic (and biotic) drivers of coastal and offshore ecosystems driven by the reduction of freshwater and sediment inflows from rivers and estuaries would affect the ecological response of coastal and offshore ecosystems* (*i.e.* develop hypotheses on the nature of the physico-chemical and ecological links in the driver-response model).

- determine the ***temporal and spatial scales (temporal and spatial resolution, duration and extent) of the measurements or modelled times series required to ensure a sufficiently robust assessment of the potential impacts of a reduction of freshwater on coastal and offshore marine ecosystems.*** This was to include:
  - the temporal and spatial scales on which a biotic (or abiotic) driver needs to be measured or that time series measurements of these drivers need to be integrated/aggregated to appropriately characterise the link between the driver and the ecological response to the driver. This could be considered to be the *spatial and temporal resolution of the driver(s) time series required as input(s) to an ecological response model.*
  - the *duration and spatial extent* of the appropriately measured or integrated/aggregated time series of driver(s) and the measure(s) of ecological response that would be required to quantify the relationships between the driver(s) and an biotic response component(s). Typically, for lower trophic levels (*e.g.* primary producers and zooplankton), a one to two year, more localised data record may be sufficient. However, for higher trophic levels the quantification of the relationships between the driver(s) and biotic response component(s) may require data sets of a 5 to 10 year duration and over a larger domain. For example, to be able to assess the impacts of freshwater reduction of certain long-lived fish stocks would required time series of a decade or more in duration while migratory fish stocks may require times series measurements over fairly spatially extensive domains covering their full life cycle.
  - The *temporal and spatial resolution of measured or modelled time series required to adequately characterise an abiotic (or biotic) driver(s) of relevance.* This could refer to direct measurements of the driver (*e.g.* sediment loads into the marine environment that typically would need to be measured on an event scale) or the measured/ modelled times series required to estimate/model the appropriate time series of the relevant driver(s) (*e.g.* event-scale flow measurements from which event scale sediment inflows to the marine environment could be estimated.)
- Based on an assessment of the availability of existing data and information, ***select appropriate measures, methods and predictive strategies for assessing the potential impacts of the reduction of freshwater inflows to coastal and offshore marine environments.***

- After the initial workshop, the CSIR was to characterise the abiotic (and biotic) drivers according to the temporal and spatial scales (temporal and spatial resolution, duration and extent) of relevance identified in the initial workshop, using numerical modelling of marine hydrodynamics and water quality. It was anticipated that the

transport and fate of nutrient and sediment discharges into the marine environment would be of greatest relevance. Of particular importance, would be the distribution and persistence of reduced salinities, elevated nutrient concentrations and turbidity in the coastal and offshore marine environments, as well as the initial deposition of sediments, their redistribution, persistence and ultimate fate in the various environments of relevance (*i.e.* nearshore zone, *etc.*). In this phase it was originally intended to undertake model simulations of the coupled estuarine/marine environment to provide environmental measures of change in the marine environment (*e.g.* changes in environmental windows, changes in extent of offshore habitats, *etc.*) that are deemed both appropriate and of sufficient temporal and spatial resolution to increase the confidence in predicted outcomes obtained from existing assessments of potential impacts in the marine environment. It was intended to use only two proxy variables to provide the measures of change, namely freshwater/nutrients treated as a conservative tracer and organic/inorganic sediments. However limited data availability and budget for this component of the project suggested a more restricted study whereby the conceptual models would be developed to the extent required to inform a basic understanding of potential mechanisms/vectors of impacts in the marine environment required for the final workshop. It was intended to use the WL| delft hydraulics hydrodynamic and water quality software for this purpose, however it was recognised after the initial workshop that an approach based on other methods may be more productively employed in these initial stages of the project. During this period, data identified during the initial workshop as being of relevance to assessing the potential impacts of the reduction of freshwater inflows to coastal and offshore marine environments, also was to be collated.

- A second and final workshop was to be held to:
  - determine the ***potential efficacy of the predictive capability provided by the added temporal and spatial information generated by limited modelling and/or interpretation of previous modelling results.*** (The workshop participants would be consulted to ensure that appropriate and simple/composite methods of presentation of the model results were adopted. Appropriate modelling results were to be disseminated to the project team prior to the final workshop so as to enable the project participants to determine the potential efficacy of using hydrodynamic and water quality modelling of the marine environment to facilitate assessments of the freshwater requirements of coastal and offshore marine environments and provide an associated predictive capability.)

  - provide the Water Research Commission with ***guidance on the nature and extent of the field work, measurement programs, studies and/or research required to ensure that the potential impacts of the reduction in***

freshwater flows into the coastal and offshore marine environments are adequately assessed when considering the desirability of proposed developments leading to the reduction of freshwater inflows to coastal and offshore marine environments.

Clearly the two workshops, while relying heavily on the collective scientific expertise of the group, were to be focussed on management issues.

- A final report would be produced summarising the outcomes of the project and providing ***recommendations on the nature and extent of the studies and/or research required*** to ensure that the potential impacts of the reduction in freshwater flows into the coastal and offshore marine environments are adequately assessed.

C.2 Revised approach and methods

After the initial workshop it became clear that there were many more unresolved issues that had not been anticipated.

Firstly, a preliminary assessment of the freshwater requirements of the coastal and offshore marine environments proved much more complex than initially anticipated. Issues that had to be resolved included:

- the difficulty in deciding upon a ***spatial domain of interest***. The boundaries of marine ecosystems are not easily defined because physical conditions and movements of organisms (*i.e.* pelagic life history stage followed by post-settlement movement to other habitats), as well as their prey, fluctuate over large distances in the sea. This complicates any assessment of potential impacts on marine environments due to changes in freshwater inflow. In estuaries the spatial domain of interest is much more easily defined.
- the difficulty in deciding upon ***one or more keystone/indicator species*** in the region of interest. This was related to the difficulty in deciding upon what are appropriate management objectives (*i.e.* what is one trying to achieve). It could be that the main objective is to maximise/protect the output from one or more commercial fisheries or to ensure a sustainable subsistence fishery. It is more likely that a broader objective is appropriate, namely that of limited change to existing ecosystem functioning and integrity as well maintenance of biodiversity. This requires a somewhat more comprehensive set of management objectives and environmental quality objectives.

- the realisation that the ***choice of a spatial domain (i.e. spatial extent of the relevant ecosystem) and one or more keystone species was somewhat of an iterative process*** and needed to be resolved.
- a ***lack of knowledge of some of the drivers and ecological response(s)*** to changes in these drivers.
- ***a lack of critical measurements required to characterise the abiotic and biotic drivers*** of relevance.
- ***confusion amongst workshop participants as to what constituted abiotic (or biotic) drivers*** (*e.g.* loads of dissolved nutrients and particulate organic matter into the marine environment, *etc.*) as opposed to ***factors that merely determine or can be used to characterise the spatial and temporal changes in the identified drivers*** (*e.g.* freshwater flows, state of the estuary mouth, *etc.*).
- The realisation during the workshop that the ***various biogeographic domains along the South African coastline are fundamentally different and would likely require different methods of assessment*** (*e.g.* the KwaZulu-Natal coastline requires a regional assessment while the assessments along the West Coast are more likely to be nodal).

The outcome of the first workshop suggested the need for a more methodical approach to the preliminary assessment and subsequent development of a suitable assessment and management framework. It would not be sufficient to simply attempt to "undertake a preliminary assessment of the freshwater requirements of the marine environment" without first considering broader issues such as the ***legislative mandate and associated management objectives*** as these determine the environmental quality objectives in a particular region and inform the selection of one or more appropriate keystone species.

Second, it was also clear from the first workshop the various biogeographic domains along the South African coastline are fundamentally different and would require different methods of assessment. For example:

- the KwaZulu-Natal coastline requires a regional assessment while along the West Coast the more limited number of rivers and estuaries and their relative remoteness from one another suggest that a nodal assessment approach is required. This implies a significantly different approach to the proposed hydrodynamic and water quality modelling in the two domains. Given the limited resources available to the project, a preliminary hydrodynamic model was to be set-up for only the KwaZulu-Natal coastline, *i.e.* the Natal Bight.

- in oligotrophic waters (KwaZulu-Natal coast) the nutrient supply associated the freshwater inflows are likely to be of greater importance, while in upwelling regions (West Coast), where dissolved nutrients are generally in adequate supply, other issues such as i) the role of freshwater plume dynamics (*e.g.* increased water column stability) in creating a favourable environment for increased water column productivity and ii) sediment and particulate organic matter discharges into the nearshore environment, are likely to be of greater importance.

From the first workshop it also became clear that the adequate characterisation of many of the drivers requires that synoptic or event scale processes are resolved in measurements or the hydrodynamic and water quality models. This in turn requires ***that freshwater and sediment inputs to the marine environment need to be quantified on an event scale.*** Presently only monthly mean flow data are readily available for the estuaries of KwaZulu-Natal, although techniques do exist for generating the simulated daily flows (*e.g.* Smakhtin, 2000) that will be required before it is possible to proceed with quantitative modelling studies. It is however possible to simulate idealised flow events (*i.e.* freshwater and sediment inflows to the marine environment associated with both base flow and flood events) and characterise their subsequent persistence and ultimate fate in the marine environment. The initial stages of the set-up of a hydrodynamic model for the Natal Bight have been completed, however it requires adequate input data before simulations can be undertaken. An initial attempt to collate such data is presently underway as a CSIR research project. The hydrodynamic model set-up will be completed and model simulations undertaken when adequate data become available.

Finally, given that the outcome form the first workshop and modelling study were somewhat different to that expected and that at best only limited modelling would be as possible, it was decided to restructure the project, particularly the final workshop. The initial workshop consumed more than 55% of the project budget and, whilst inclusive, allowed for little direct contact time between the various participants. Instead of holding a second large workshop it was decided to distribute the summary of the first workshop contained in a draft of this report to selected members of the original project team for review and to obtain focussed inputs to the final assessment and recommendations on the nature and extent of the studies and/or research required to assess the freshwater requirements of coastal and offshore marine environments. The smaller group also allows for easier scheduling of the inputs to the project, an issue that proved particularly problematic for the first workshop.

APPENDIX D:
Summary of outcomes of the initial workshop

Summary of the initial two day workshop

The format, contributors and outcomes of the initial two workshops are summarized below.

D1 Workshop Agenda

The preliminary workshop Agenda was as follows:

Preliminary Agenda
Freshwater Requirements of the Marine Environment
Stellenbosch, Botanical Gardens
11 –12 December 2003

Day 1 (11 December 2003)

9:00 – 9:30	*Coffee/Tea*
9:30 – 10:00	*Welcome*
10:00 – 11:00	*Background*
11:00 – 11:20	*National Water Act*
11:20 – 11:40	*Coffee/Tea*
11:40 – 12:00	*Driver Response Approach*
12:00 – 1:30	**Freshwater Reduction Impacts: South African examples**
1:30 – 2:30	*Lunch*
2:30 – 3:30	*Freshwater Reduction Impacts: South African examples (continued..)*
3:30 – 3:45	*Coffee/Tea*
3:45 – 5:30	*Biophysical / Ecological Function Framework*

Day 2 (12 December 2003)

8:30 – 8:45	*Allan Connell: Fish larvae and freshwater input*
8:45 – 9:00	*Steve Lambert: A South African approach - Thukela Marine Study*
9.00 – 9:15	*Andre Theron: Sediment and freshwater inflow*
9:15 – 10:30	*Biophysical / Ecological Functioning - critical links by region*
10:30 – 11:00	*Coffee/Tea*
11:00 – 1:00	*Information availability/requirements (temporal and spatial scales)*
1:00 – 2:00	*Lunch*
2:00 – 3:00	*Information availability/requirements (temporal & spatial scales) continued.*
3:00 – 3:20	*Coffee/Tea*
3:20 – 4:00	*Closure: Synopsis of workshop and way forward*

D2 Workshop Attendees

Ms Christine Colvin	CSIR
Dr Alan Connell	CSIR
Dr Nicolette Demetriades,	Marine and Estuarine Research
Mr Sean Fennessy	Oceanographic Research Institute
Professor Ticky Forbes	Marine and Estuarine Research
Mr Mthuthuzeli Gulekana	CSIR
Mr Johan Groeneveld	Marine and Coastal Management, DEAT
Mr Pieter Huizinga	Private Consultant
Mr Stephen Lamberth	Marine and Coastal Management, DEAT
Mr Pat Morant	CSIR
Professor Renzo Perisinotto	Marine and Estuarine Research
Dr Trevor Probyn	Marine and Coastal Management, DEAT
Dr Nadine Strydon	South African Institute for Aquatic Biodiversity*
Ms Susan Taljaard	CSIR
Mr Andre Theron	CSIR
Mr Roy van Ballegooyen	CSIR
Ms Lara van Niekerk	CSIR
Professor Tris Wooldridge	University of Port Elizabeth

* Dr Nadine Strydom was not able to attend the workshop but provided a written contribution

The following persons have contributed to the report via discussion, comment and contributions that took place after the workshop:

Dr Pedro Monteiro	CSIR
Mr Camaren Peter	CSIR
Mr Steven Weerts	CSIR

D3 Workshop Outcomes and Notes

The outcomes and notes from the workshop are summarised below in terms of:

- Ecological responses to abiotic (and biotic) drivers (Tables D.1 to D4)
- Temporal and spatial scales of relevance
- Measurement techniques
- Research Needs
- National and international research initiatives of relevance

D3.1 Ecological responses to abiotic (and biotic) drivers

Table D.1 Subtropical region: Sensitivity of ecological response categories to abiotic and biotic drivers affected by changes in freshwater inflows into the marine environment

	Phytoplankton	*Benthic algae*	*Holozooplankton (adults)*	*Benthic Invertebrates*	*Fish*	*Birds*	*Mammals*	*Turtles*	*Shoreline & Beach Erosion*
Estuarine habitat									
Mouth condition									
Cueing effects									
Fronts	*1*			*1*	*3*	*3*	*3*		
Salinity	*3*	*3*	*2*	*3*	*3*				
Temperature									
Turbidity			*2*			*2*			
Sediment particle size		*2*	*1*						
Sediment load		*2*	*1*		*3*			*3*	
Dissolved nutrients									
POM									
Phytoplankton				✓	✓				
Benthic algae			✓	✓	✓			✓	
Zooplankton			✓	✓	✓	✓			
Benthic Inverts			✓	✓	✓	✓		✓	
Fish			✓	✓	✓	✓	✓	✓	
Birds									
Mammals									

Red = Highly sensitive drivers
Orange = Medium sensitive drivers
Yellow = Low sensitive drivers

3 = High Confidence
2 = Medium Confidence
1 = Low Confidence

Table D.2 **Subtropical region: Nature of the response of ecological response categories to abiotic drivers affected by changes in freshwater inflows into the marine environment, and trophic linkages**

	Phytoplankton	***Benthic algae***	***Holozooplankton (adults)***	***Benthic Invertebrates (includes larval stage, i.e. meroplankton)***	***Fish***	***Birds***	***Mammals***	***Turtles***	***Shoreline & Beach Erosion***
Estuarine habitat	-	-	-	*Estuarine dependent species, e.g. crabs, prawns immature stages use the estuary –Veruna*	*Estuarine dependent species*	-	-	-	-
Mouth condition	-	-	-	*Immigration/ emigration*	*Immigration/ emigration Recruitment*	-	-	-	-
Cueing effects	-	-	*No evidence*	*Some require this not all, we need to still research this*	*Cueing to spawning immigration*	-		-	-
Fronts (and stratification)	*Retaining the euphotic zone*	-	*Feed on accumulated biomass of phytoplankton at fronts*	*Will affect larval stages of all There are 'front' specialist species)*	*Hide along dirt fronts to avoid predation and provide concentrated areas 'food'*	*Feeding off freshwater fronts*	*Cue for feeding*	-	-
Salinity	*Salinity tolerance*	*Salinity tolerance*	*Salinity tolerance*	*Salinity tolerance*	*Salinity tolerance*	-	-	-	-
Temperature	***Not a driver in KZN as estuarine and marine temperatures are not significantly different.***								
Turbidity	*Change in light availability*	*Change in light availability*	*Change movement behaviour*	*Habitat preferences may be altered (light response) larvae move up and down*	*Habitat related Predation influenced – can't see prey*	*Predation/ Feeding habits related to colour changes*	*Habitat preferences thus change distribution*	-	-
Sediment particle size		*Distribution of species and abundance*	*Inorganic particles can interfere with feeding*	*Habitat preferences*	*Habitat alteration*	-	-	-	*Erodability issue*
Sediment load	-	*Smothering/ Scouring*	-	*Smothering/ erosion Change in habitat*	*Smothering/ erosion Change in*	-	-	*Alteration of habitat*	*Alteration of sedimentation and erosion processes*

	Phytoplankton	Benthic algae	Holozooplankton (adults)	Benthic Invertebrates (includes larval stage, i.e. meroplankton)	Fish	Birds	Mammals	Turtles	Shoreline & Beach Erosion
					habitat Clogging of gills				
Dissolved nutrients	Production alterations	Production alterations	-	-	-	-	-	-	-
POM	-	-	Algae (POM) produced in estuary during e.g. mouth closure	Food supply	Food source	-	-	-	-
Phytoplankton			Food	Food	Food				
Benthic algae			Food s	Food	Food			Food	
Zooplankton			Food/ competition	Food	Food	Food			
Benthic Inverts			Food (eggs/ larvae)	Food	Food	Food		Food	
Fish			Food (eggs/ larvae)	Food	Food	Food	Food	Food	
Birds									
Mammals									

Table D.3 Cool temperate region: Sensitivity of ecological response categories to abiotic and biotic drivers affected by changes in freshwater inflows into the marine environment

	Phytoplankton	*Benthic algae*	*Holozooplankton (adults)*	*Benthic Invertebrates*	*Fish*	*Birds*	*Mammals*	*Turtles*	*Shoreline & Beach Erosion*
Estuarine habitat						3		n/a	
Mouth condition								n/a	
Cueing effects								n/a	
Fronts			3*					n/a	
Salinity	3*	3*						n/a	
Temperature	3*	3*	3*	*				n/a	
Turbidity	3*	3*						n/a	
Sediment particle size		3*						n/a	3*
Sediment load		3*			2			n/a	2*
Dissolved nutrients	3*	3*						n/a	
POM								n/a	
Phytoplankton	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Benthic algae	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Zooplankton	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Benthic Inverts	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Fish	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Birds	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed
Mammals	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed	not assessed

***The table for the West Coast has been assessed on a inshore (localised) scale, *i.e.* effects are localised.**

Red = Highly sensitive drivers
Orange = Medium sensitive drivers
Yellow = Low sensitive drivers

3 = High Confidence
2 = Medium Confidence
1 = Low Confidence

Table D.4 **Subtropical region: Nature of the response of ecological response categories to abiotic drivers affected by changes in freshwater inflows into the marine environment, and trophic linkages**

	Phytoplankton	*Benthic algae*	*Holozooplankton (adults)*	*Benthic Invertebrates (includes larval stage, i.e. meroplankton)*	*Fish*	*Birds*	*Mammals*	*Turtles*	*Shoreline & Beach Erosion*
Estuarine habitat	-	-	-		*Estuarine dependency*	*Nesting & Roosting*			
Mouth condition	-	-	-		*Refuge areas, e.g. from low O_2 conditions*				
Cueing effects	-	-	-		*Cue to be able to get to a refuge and/or nursery area*				
Fronts (and stratification)	*Highly stratified conditions due to river plumes may lead to bloom conditions if nutrients are in adequate supply*	-	*May be important at the larger rivers, e.g. Orange, feeding frenzies at fronts*						
Salinity	*Trivial localised impacts*	*Trivial localised impacts*							
Temperature	*Trivial localised impacts*	*Trivial localised impacts*			*Creates an enhanced nearshore habitat*				
Turbidity	*Trivial localised impacts*	*Trivial localised impacts*			*Creates an enhanced nearshore habitat*				

	Phytoplankton	Benthic algae	Holozooplankton (adults)	Benthic Invertebrates (includes larval stage, i.e. meroplankton)	Fish	Birds	Mammals	Turtles	Shoreline & Beach Erosion
Sediment particle size		*Trivial localised impacts*			*Sediment load create habitat, esp for flatfish species.*				*Erodability*
Sediment load		*Trivial localised impacts*							*Localised shoreline effects near the mouth if loads are changed*
Dissolved nutrients	*Localised, e.g. groundwater input into Langebaan*	*Localised, e.g. groundwater input into Langebaan*							
POM					*Food source*				
Phytoplankton	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Benthic algae	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Zooplankton	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Benthic Inverts	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Fish	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Birds	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*
Mammals	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*	*not assessed*

D3.2 Temporal and spatial scales of relevance

The temporal and spatial scales of relevance include those required to research the relationships between abiotic (and biotic) drivers and the ecosystem response and those required to monitor and/or manage marine ecosystems in terms of their freshwater requirements.

The temporal and spatial resolution at which a driver needs to be measured/simulated depends on the variability in the driver, both at sea (e.g. natural signals) and in river inflow. The temporal and spatial resolution has to be adequate to avoid aliasing of any signal when integration temporally and spatially to match the response temporal and spatial response scales of the related biotic response. The time series of measured drivers and response variables needs to be of adequate duration to have confidence in the indicated relationships between the driver and response variables.

Thus the temporal and spatial scales of relevance are:

- **the temporal and spatial scales that need to be resolved in order to adequately characterise the drivers:** The temporal scale at which a driver needs to be measured/simulated depends on the variability in the driver, both at sea and in river inflow. Drivers associated with the water column (*e.g.* dissolved nutrients) typically have variability of hours to days to weeks. Drivers associated with the sediments (*e.g.* particle size distribution defining a habitat) typically show variability of weeks to seasons to decades, depending on the deposition/re-suspension characteristics of the study area.
- **the temporal and spatial scales at which the biota responds to the various drivers:** The various abiotic (and biotic) drivers need to be integrated and/or aggregated, such that they are relevant to determining the biotic response, *i.e.* they need to be integrated on temporal scales similar to the biological response times and aggregated over spatial scales over which this biological response occurs. For example, elevated nutrient[39] levels need to persist in the marine environment for days to weeks for there to be a significant response in phytoplankton and benthic micro/macro algae.
- **the duration and spatial extent of the data record required to adequately characterise the drivers and to quantify the relationships between driver(s) and the biotic response:** For example, to be able to predict the relationship between the "state of the mouth" and river flow, a data record of between 5-10 years of daily recordings of both parameters will be required. Typically for lower trophic levels, *e.g.* primary producers and zooplankton, a relatively high resolution of 1 to 2 year data record may be sufficient. However, for higher trophic levels these may require data sets extending over 5 to 10 years or preferably more.

In Table D.5 the relevant temporal and spatial scales are listed in the following order:

i) temporal and/or spatial resolution required to adequately characterise the abiotic (and biotic) drivers. These may include direct measurements of the relevant drivers or

[39] Note: Dissolved nutrients for primary producers need to include DIN, DIP, DIS, DON (not DOC for primary producers)

measurements of other variable that are used to characterise the drivers, e.g. the resolution of flow rates and nutrient concentrations in estuarine outflows needed to characterise nutrient loads into the marine environment.

ii) the duration and spatial scale of aggregation/integration of the driver signals required to assess the biotic response, i.e. the drivers need to be integrated on temporal scales similar to the biological response times and aggregated over spatial scales over which this biological response occurs.

iii) The minimum period over which a significant biotic response can be expected (in brackets where listed).

Examples of the relevant scales are:

- Primary producers (all parameters)
  - Microalgae: Daily measurements to characterise drivers on event scales. Expected response time of microalgae being within days;
  - Macroalgae: Minimum weekly measurements to roughly characterise drivers on event scale, however the expected response time of macroalgae being weeks/months);
  - Benthic algae: Here there is a need to resolve deposition/erosion events, thus preferably daily to weekly measurements (particle size/sediment load) are required to characterise drivers on event scales. Here event scales may be storms occurrences rather than regular weather events.
- Zooplankton: Ideally daily sampling (all parameters) is required to characterise drivers on event scales. Response times vary.
  - Response: Grazing respond about two weeks or longer (4 weeks)
  - Response: Smaller copepods about three days response
  - Response to turbidity: Daily response in behaviour

Table D.5: **Temporal and spatial scales of relevance in researching the relationships between abiotic (and biotic) drivers and the ecosystem response and those required to monitor and/or managing marine ecosystems in terms of their freshwater requirements**

	Phytoplankton	Benthic algae	Holozooplankton (adults)	Benthic Inverts	Fish	Birds	Mammals	Turtles	Shoreline & Beach Erosion (Development)
Estuarine habitat				*Daily flows - Mouth conditions integrated to be monthly*	*Daily flows - Mouth conditions integrated to be monthly*				
Mouth condition				*Daily flows - Mouth conditions integrated to be monthly*	*Daily flows - Mouth conditions integrated to be monthly*				
Cueing effects				*Daily spatial scale of plume*	*Presence and size of plume in a month*				
Fronts	*Daily Duration–event (Significant- days)*		*Daily Duration–event (Significant- days)*	*Daily Duration–event (Significant- 1 to 4 week), Larvae*	*Presence and size of plume in a month*	*Daily Duration–event (Significant- 1 to 4 week),*	*Presence and size of plume in a month*		
Salinity	*Daily Duration–event (Significant response- days)*	*Daily Duration–event (Significant responset- days (micro)-weeks (macro))*	*Daily Duration–event (Significant response - 1 to 4 week)*	*Daily Duration–event (Significant response t- 1 to 4 week) Larvae*	*Presence and size of plume in a month*				
Temperature*	*Daily measurements to characterise drivers on event scales*	*Daily measurements to characterise drivers on event scales*	*Daily measurements to characterise drivers on event scales*		*Daily measurements to characterise drivers on event scales*				

	Phytoplankton	Benthic algae	Holozooplankton (adults)	Benthic Inverts	Fish	Birds	Mammals	Turtles	Shoreline & Beach Erosion (Development)
Turbidity	*Daily Duration–event (Significant response - days)*	*Daily Duration–event (Significant response - days (micro)-weeks (macro))*	*Daily Duration–event Behavioural response*	*Daily (larval) weekly Duration–event Behavioural Monthly (Spatial)*	*Presence and size of plume – daily Monthly (Significant response – months Multi-years)*	*Daily Duration–event (Significant response - 1 to 4 week),*	*Presence and size of plume – monthly (Significant response – months Multi-years)*		
Sediment particle size		*Daily Duration–event (Significant-days (micro)-weeks (macro))*	*weekly Duration–event (Significant- 1 to 4 week)*	*weekly Duration–event (Significant- 1 to 4 week)*	*Monthly (Significant – multi-years)*				*Continuous for 20 years (Weeks to years)*
Sediment load		*Daily Duration–event (Significant response - days (micro)-weeks (macro))*	*weekly Duration–event (Significant response- 1 to 4 week)*	*weekly Duration–event (Significant response – 1 to 4 weeks)*	*Monthly significant response – multi-years)*			*Annual for 20 years*	*Annual for 20 years (Weeks to years)*
Dissolved nutrients	*Daily Duration–event (Significant response - days)*	*Daily Duration–event (Significant response – days (micro)-weeks (macro))*							
POM			*daily Duration–event (Significant response – 1 to 4 week)*	*daily Duration–event (Significant response – 1 to 4 weeks)*	*Monthly (Significant response – multi-years)*				

Red = Highly sensitive drivers Orange = Medium sensitive drivers Yellow = Low sensitive drivers

* Temperature is only considered to be of relevance on the West Coast.

D3.3 Measurement Techniques

Potential measurement techniques to obtain the relevant data are listed below. The role of hydrodynamic and water quality modelling in providing information at the relevant temporal and spatial scales is included here.

Estuarine habitat: A complex set of measures, indices is required.

Mouth Condition: Mouth condition data is not readily available. Ideally daily observations of mouth condition by observer(s) or water level recordings in mouth. Water level recording will not indicate outflows from a perched estuary and/or berm overtopping. A knowledge of flows and metocean conditions (daily) may help to characterise mouth states (Theron and Bergman, 2007).

Cueing effect: Flow and mouth condition can be used as a proxy measure for cueing effect and, as indicated above, this would require flow gauges and water level recorders/daily observations). Furthermore the likely extent and duration of the cueing effect could be characterised using estimated river outflows and nearshore modelling of metocean conditions.

Fronts: Flow and mouth condition can be measured as a very rough proxy for the likely extent of frontal systems in the marine environment. (This would require flow gauges and water level recorders/daily observations). However to obtain a relatively robust estimate of the duration and extent of these features would require additional data/modelling as follows:.

- Salinity and temperature profiles for selected periods using in-situ temperature and salinity profiles and/or moorings (e.g. thermistor chains) providing time series at selected locations.
- Remote sensing techniques, e.g. colour (KZN) or temperature (West Coast), visual wave band (e.g. turbidity showing extent of plume – this will not be quantitative data)

Salinity: In-situ measurement using standard CTD equipment and/or moorings. Possibly new remote sensing techniques are available to provide such measurements?

Temperature: Temperature profiles using in-situ profilers (e.g. thermistor chains), may acquire time series for selected periods. Alternatives are remote sensing techniques, e.g. infra-red remote sensing of sea surface temperature that is likely to be best undertaken on the West Coast. Ocean colour measurements are likely to be more useful on the east coast where sea surface temperature contrasts are likely to be small.

Turbidity: In-situ measurements of suspended sediments. Surface turbidity could be measured using remote sensing techniques in the visual wave band (e.g. turbidity showing extent of plume – will not be quantitative data). Time series measurements could be obtained from moored buoy systems (e.g. SEAWATCH).

Sediment particle size: Shoreline has been sampled quite intensively, but no central database exists to collate and manage these data. Should this be developed? Only limited sub-tidal exist, linked to specific projects. There is a requirement to investigate whether ADCP can be used to gather information on particle size. Sources of existing data could be:

- MCM offshore cruises
- Marine Geo survey
- UCT Geoscience
- Burg Flemming's old data sets (are they still available?)
- More recent WESSA-sponsored measurements

Sediment loads: Bathymetric surveys are available for limited areas. Aerial photos exist for analysis of shoreline erosion and accretion. There is only limited sub-tidal information in terms of deposition, however there exist possible data sources as listed above. It is possible that suspended sediments concentrations in water samples can provide a (limited) proxy for likely nodes of deposition of sediments in the marine environment.

Dissolved nutrients: Sources of data could include nitrate probe mooring/profiler (?) and standard sampling of nutrients for measurements in the marine environment. Chlorophyll can also be sued as proxy for nutrients where nutrients are overriding factor that influence phytoplankton production (However, it would be difficult to discern marine and terrestrial inputs – possibly use stable isotope analysis?). To estimate nutrient fluxes from estuaries to the marine environment requires both flow and nutrient concentration estimates/measurements at estuary mouths.

POM: Possible use of remote sensing techniques, e.g. visual wave band (not quantitative data), however such data would only be indicative of what is occurring near the surface. Possible mooring observations (however there will be requirements to determine terrestrial versus marine sediments – possibly using stable isotope analysis?).

D3.4 Research Needs

The following were the research needs identified at the workshop:

- Investigate whether freshwater requirements need to be looked at a regional level rather than an individual level. Presently this is the focus of a CSIR research programme.
- Determine on relevant time scales the fluxes of nutrients and sediments into the marine environment.
- Determine the relative importance terrigenous and marine sources of nutrients, detritus *etc.* (*e.g.* using stable isotopes)
- Assess in greater detail the inshore, localised influence of river inputs on the West coast, *e.g.* how does this ripple through to the commercial gill net and beach seine fisheries
- Determine the magnitude of (particularly West coast) groundwater inputs and the significance thereof.
- Cueing effect – what is providing the signal?
- Better characterise nearshore dynamics (CSIR has done some of this, it just needs to be utilised/published!)
- Determine the sediment dynamics on the shelf along the south and west coast. Information exists on sediment pattern movement along the East Coast as far south as Port Elizabeth (Burg Flemming). It will be important is to get simultaneous hydrodynamic data to make the links allowing predictions to be made.

D3.5 National and International Research Programmes of Relevance

National and International programmes that potentially could support research into the freshwater requirements of the marine environment include:

- LOICZ (Land-Ocean Interactions in the Coastal Zone);
- GPA (Global Programme of Action for the protection of the marine environment against land-based activities);
- WIO-lab (Western Indian Ocean Land-based Activities);
- ACEP (African Coelacanth Ecosystem Programme);
- ASLME (Agulhas-Somali Large Marine Ecosystem);
- EU (European Union)-funded projects;
- Coastal GOOS/AfriGoos (Global Ocean Observing Systems);
- BENEFIT (Benguela Environmental Fisheries Interaction and Training) programme: Orange-Kunene studies;
- BCLME (Benguela Current Large Marine Ecosystem) programme: Orange River studies;

- SEAWATCH;
- MCM (Marine and Coastal Management) research programmes collecting data;
- Universities – typically short-term intensive data sets used for MSc or PhD (*e.g.* work done opposite the Kosi system through Branch);
- Large coastal municipalities collecting shoreline stability, sediment and water quality data. However there may be concerns around the quality of these data;
- Coast Care.