

# An Evaluation of the Ecological Flow Requirements of South Africa's Estuaries from a Hydrodynamics Perspective

Report to the  
**WATER RESEARCH COMMISSION**

by

**LARA VAN NIEKERK, SUSAN TALJAARD & PIET HUIZINGA**

with contributions from

**AK Theron, SM Bergman & R van Ballegooyen**

**WRC Report No. KV 302/12**

**ISBN 978-1-4312-0328-4**

**September 2012**

**Obtainable from**

Water Research Commission  
Private Bag X03  
GEZINA, 0031

[orders@wrc.org.za](mailto:orders@wrc.org.za) or download from [www.wrc.org.za](http://www.wrc.org.za)

The publication of this report emanates from a project titled An Evaluation of the Ecological Flow Requirements of South Africa's Estuaries from a Hydrodynamics Perspective (WRC Project No. K8/787).

**DISCLAIMER**

This report has been reviewed by the Water Research Commission (WRC) and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

## **TABLE OF CONTENT**

<b>1. INTRODUCTION</b>	<b>1</b>
<b>2. LEGISLATIVE SUPPORT FOR ENVIRONMENTAL FLOW REQUIREMENTS IN SOUTH AFRICA</b>	<b>3</b>
2.1 THE NEED FOR NEW LEGISLATION	3
2.2 RELEVANT SECTIONS IN THE NATIONAL WATER ACT 36 OF 1998 FROM AN ESTUARY PERSPECTIVE	5
2.2.1 LEGAL DEFINITIONS	5
2.2.2 DELEGATION OF POWER	5
2.2.3 SPECIFIC PROVISIONS TO MITIGATE THREATS TO GOODS AND SERVICES PROVIDED BY ESTUARIES	5
2.3 EFFECTIVENESS OF THE NATIONAL WATER ACT	7
2.4 HYDRODYNAMIC REQUIREMENTS FOR ESTUARIES	8
<b>3. HISTORICAL OVERVIEW</b>	<b>10</b>
3.1 ENGINEERING APPROACHES DEVELOPED IN THE 1980S	10
3.2 FIRST ESTUARINE FLOW REQUIREMENTS (EFR) STUDIES IN SOUTH AFRICA	11
<b>4. INTERNATIONAL EWR APPROACHES APPLIED TO ESTUARIES</b>	<b>14</b>
<b>5. PHYSICAL PROCESSES AT PLAY IN AN ESTUARY</b>	<b>17</b>
5.1 ESTUARINE CLASSIFICATION BASED ON HYDRODYNAMICS FEATURES	17
5.2 ESTUARINE RESPONSE OF TO MODIFICATION IN RIVER INFLOW	17
5.2.1 PERMANENTLY OPEN ESTUARIES	17
5.2.2 TEMPORARILY OPEN/CLOSED ESTUARIES	18
5.3 SENSITIVITY TO FLOW REDUCTION	19
5.3.1 OPENING FORCES (MAINTAIN OPEN MOUTH CONDITIONS)	19
5.3.2 CLOSING FORCES	20
<b>6. WATER LEVELS</b>	<b>22</b>
6.1 TIDAL AMPLITUDES AND BERM HEIGHTS	22
6.2 PROPOSED METHOD FOR ESTIMATING BERM DEVELOPMENT	23
<b>7. MOUTH STATE</b>	<b>25</b>
7.1 BALANCE OF WATER VOLUME IN A CLOSED ESTUARY	25

7.1.1	SIMPLIFICATION OF THE WATER BALANCE	26
<b>7.2</b>	<b>APPLICATIONS OF THE WATER BALANCE MODEL IN EWR STUDIES</b>	<b>28</b>
7.2.1	ST LUCIA	28
7.2.2	SWARTVLEI	29
7.2.3	MDLOTI, MLANGA AND GREAT BRAK	31
7.2.4	LITTLE AMANZINTOTI AND MBOOKEDWENI	31
<b>7.3</b>	<b>PROTOTYPE MODEL THAT LINKS RIVER INFLOW TO BERM HEIGHT</b>	<b>32</b>
7.3.1	MODEL CONCEPTUALISATION AND FORMULATION	32
7.3.2	RESULTS	34
7.3.3	CONCLUSIONS AND RECOMMENDATIONS	36
<b>8.</b>	<b><u>SALINITY PENETRATION</u></b>	<b><u>38</u></b>
<b>8.1</b>	<b>MEASURE DATA/CORRELATION APPROACH</b>	<b>39</b>
<b>8.2</b>	<b>SALT BALANCE MODEL</b>	<b>40</b>
<b>8.3</b>	<b>ONE DIMENSIONAL (1D) NUMERICAL MODELLING</b>	<b>40</b>
<b>8.4</b>	<b>THREE DIMENSIONAL (3D) NUMERICAL MODELLING</b>	<b>41</b>
<b>8.5</b>	<b>SELECTING THE CORRECT MODELLING APPROACH</b>	<b>47</b>
<b>8.6</b>	<b>RETENTION TIME</b>	<b>49</b>
<b>9.</b>	<b><u>AN ECOHYDROLOGICAL METHOD FOR DETERMINING ESTUARINE FLOW REQUIREMENTS, AN SOUTH AFRICAN APPROACH</u></b>	<b><u>51</u></b>
<b>9.1</b>	<b>DESCRIBE CATCHMENT AND GENERATE SIMULATED HYDROLOGICAL RECORD</b>	<b>52</b>
9.1.1	DESCRIBE THE CATCHMENT CHARACTERISTICS	52
9.1.2	GENERATE HYDROLOGICAL RECORD	52
9.1.3	STATISTICAL INTERROGATION	53
<b>9.2</b>	<b>IDENTIFY ABIOTIC STATES</b>	<b>55</b>
<b>9.3</b>	<b>IDENTIFY CHANGES IN ABIOTIC STATES</b>	<b>59</b>
<b>9.4</b>	<b>PREDICT CHANGES THE BIOTIC COMPONENTS OF THE ESTUARINE ECOSYSTEM</b>	<b>60</b>
<b>9.5</b>	<b>SEDIMENT PROCESSES</b>	<b>61</b>
<b>9.6</b>	<b>DISCUSSION</b>	<b>62</b>
9.6.1	SCALES	62
9.6.2	EFFECTS OF DATA ON CONFIDENCE	62
<b>9.7</b>	<b>ANTHROPOGENIC INFLUENCE</b>	<b>62</b>
<b>10.</b>	<b><u>PRINCIPALS OF ESTUARINE ENVIRONMENTAL FLOWS REQUIREMENTS STUDIES</u></b>	<b><u>64</u></b>
<b>11.</b>	<b><u>RECOMMENDATIONS FOR IMPROVEMENT OF THE ABIOTIC COMPONENT OF THE RDM METHODS</u></b>	<b><u>66</u></b>
<b>11.1</b>	<b>HYDROLOGY</b>	<b>66</b>
<b>11.2</b>	<b>HYDRODYNAMICS</b>	<b>66</b>

<b>11.3 WATER QUALITY</b>	<b>67</b>
<b><u>12. REFERENCES</u></b>	<b><u>68</u></b>

---

## **LIST OF FIGURES**

Figure 3-1 Simplified hydrographs of the 2 year flood indicating the differences between a large and small catchments (Source: Jezewski and Roberts, 1986). .....	10
Figure 3-2 Simulated water levels and tidal exchange data generated for Great Brak Estuary EFR study in 1990 (CSIR, 1990).....	13
Figure 6-1 Mouth position on berm (perched, non-perched) in South Africa’s estuaries (Modified from Cooper, 2001). .....	22
Figure 7-1 Water Balance in a closed estuary .....	26
Figure 7-2 Mean annual potential evaporation (mm) A-pan Equivalent (Schulze and Maharaj, 2007).27	
Figure 7-3 Relationship between water level at breaching (DWA STATION K4R002) and days open....	30
Figure 7-4 The Groot Brak Estuary .....	32
Figure 7-5 The Groot Brak Estuary Mouth just after (assisted) breaching .....	33
Figure 7-6 Combined plot of predicted and actual water levels in the Estuary and Berm Height over time Seepage and Evaporation effects are included.....	34
Figure 7-7 Combined plot of actual and predicted water levels in the estuary and Berm Height over time. Seepage and Evaporation are not included. ....	35
Figure 7-8 Measured water level at the time of breach of the Groot Brak Estuary against the calculated value for berm height using the Swart (blue diamonds) as well as the Nielsen & Hanslow (red triangles) methods.....	36
Figure 8-1 Vertically-integrated salinity distribution in the Great Berg Estuary from 2003 to 2005 representative of a particular seasonal distribution (DWAf, 2010). Also indicated on the graphs are the different zones and .....	39
Figure 8-2 Observed longitudinal salinity distributions in Knysna Estuary at high tide on 10 March 1984.....	45
Figure 8-3 Simulated longitudinal salinity distributions in Knysna Estuary at high tide on 10 March 1984.....	45
Figure 8-4 Observed longitudinal salinity distributions in Knysna Estuary at low tide on 26 October 1996.....	46
.Figure 8-5 Simulated longitudinal salinity distributions in Knysna Estuary at low tide on 26 October 1996.....	46
Figure 8-6 A robust decision tree to decide on to type of numerical model to be used for a particular application in estuaries (1D = one dimensional; 2D = two dimensional; 2Dh = two dimensional horizontal; 3D = three dimensional) (Van Ballegooyen et al., 2004).....	48

Figure 9-1 Summary of typical physical and water quality characteristics of different abiotic states in the Palmiet Estuary (DWAF, 2010) .....57

Figure 9-2 Schematic representation of the key circulation features of the five abiotic states of the Palmiet Estuary (after Van Ballegooyen et al., 2004) .....58

Figure 9-3 Option for summarising the seasonal distribution of flows, particularly for estuaries where variations within months are stronger than seasonal variation.....60

**LIST OF TABLES**

Table 7.1 Summary of model results indicating days to breaching and predicted berm height.....35

Table 8.1 Example of the estimated duration of the persistence of low salinity conditions in the Knysna Estuary due to various inflow conditions.....44

Table 9.1 Potential indices of hydrological change that can be applied to SA catchments .....54

Table 9.2. Example of estimated monthly flows and occurrence and duration of different abiotic states for the Palmiet Estuary under the Present State flow scenario .....59

Table 9.3 Example of summary of monthly flows and occurrence and duration of different abiotic states for the Palmiet Estuary under the Present State flow scenario.....60

## **LIST OF APPENDIXES**

Appendix A	POLICIES, ACTS AND GUIDELINES APPLICABLE TO SA ESTUARIES
Appendix B	DETAILED CASE STUDY: BREEDE ESTUARY EWR
Appendix C	SUMMARY OF THE ABIOTIC STATES IDENTIFIED IN HISTORICAL ECOLOGICAL FLOW REQUIREMENTS STUDIES
Appendix D	DATA REQUIREMENTS



## 1. INTRODUCTION

South Africa has a relatively high energy coastline, with few sheltered embayments. In addition South Africa's climate ranges from semi-arid to hyper-arid with only a few relatively humid parts where rainfall greatly exceeds 500 mm annually (Davies and Day, 1998). South Africa therefore has comparatively low runoff for its surface area.

In the international literature, an estuary is defined as 'a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land' (Cameron & Pritchard, 1963; Pritchard, 1967). South Africa's estuaries are relatively small in comparison with those of the northern hemisphere and the country's rivers runoff is more variable, fluctuating between floods and extreme low, to no, river inflow. This combination of relatively small size and low runoff, coupled with extreme environmental conditions, such as droughts, had lead to a number of different definitions for South African estuaries (Day, 1980, Heydorn, 1989). The most comprehensive definition for a South African estuary is the one outlined in the South African National Report (CSIR, 1992) for the United Nations Conference on the Environment and Development held in Rio de Janeiro, June 1992:

*'In South African an estuary is considered to be that portion of a river system which has, or can from time to time have, contact with the sea. Hence, during floods an estuary can become a river mouth with no seawater entering the formerly estuarine area. Conversely, when there is little or no fluvial input an estuary can be isolated from the sea by a sandbar and become a lagoon which may become fresh, or hypersaline, or even completely dry.'*

An estuary is largely determined by the river flow it receives in all its variability from major floods to low flows. Changes in river flow in principle will affect the functioning and production of an estuary, and ultimately the ecosystem service society derived from them (Hutchings et al., 2010; Lamberth et al., 2008; Whitfield et al., 2008; Adams et al., 2002). However, the needs for water for agriculture, domestic and industrial use are also recognized and, in principle, an optimum balance needs to be established between the changes (often reductions) in river flow and the (often negative) effects on the environment.

The recognition that estuaries need freshwater to maintain their health and productivity and the methodology on how to determine their ecological flow requirements is a relatively new field of study (Hirji and Panella, 2003). Environmental flows refer to the water regime of a river, wetland or coastal zone necessary to maintain the biophysical components, ecological processes and health of aquatic ecosystems and associated ecological goods and services (Arthington et al., 2006). The concept of Environmental Flows is rapidly developing into a suite of frameworks, methods and tools for the protection, and even restoration, of inland and coastal aquatic ecosystems (Naiman et al., 2006). The determination of ecological flow requirements is underpinned by the emerging discipline of ecohydrology, which straddles a range of engineering and scientific disciplines and borrows from approaches and technologies developed for rivers, estuaries and the marine environment.

The discipline of ecohydrology explicitly recognises the need for (Naiman et al., 2006; Hannah, Wood and Sadler, 2004; Brown, 2002; Parr et al., 2003):

- (1) An understanding of hydrological/ecological interactions and stresses the importance of feedback mechanisms;

- (2) a fundamental process understanding of driver-response relationships in contrast with simple functional (statistical) links;
- (3) an understanding of process interactions at a range of spatial and temporal scales;
- (4) the study scope to include the full range of (natural and human-impacted) water-dependent habitats encompassing the whole ecosystem; and
- (5) the multidisciplinary or interdisciplinary nature of the research.

Three main countries have developed environmental flow assessment methods for estuaries, i.e. South Africa, Australia and the USA. Methods have mostly developed from practical applications, a learning-by-doing approach, with most approaches including elements of risk assessment and adaptive management. The majority of approaches are data rich and emphasize long-term monitoring so that the impacts of freshwater inflow alteration can be understood. Where water resources development has required a high degree of certainty, detailed modelling and monitoring exercises were conducted to inform the decision making process (Adams in prep).

This document sets out to describe the development of the South African estuarine ecological flow requirements methods from a hydrodynamics perspective, with an emphasis on the last decade – 2000 to 2010. The document reviews the historical development of the method. It discusses the approaches to evaluating berm heights, mouth conditions, water levels and salinity changes. It then highlights the concepts of integrated abiotic states linked to flow ranges. The document concludes with some recommendation for future updates of the estuary EWR methods in South Africa.

Appendix A provides a summary of the environmental legislation supporting the process, while Appendix B provides a detail summary of the approach followed in the Breede Estuary assessment. Appendix C provides the abiotic process data requirements of the South African EWR methods to increase the overall confidence of an assessment.

## 2. LEGISLATIVE SUPPORT FOR ENVIRONMENTAL FLOW REQUIREMENTS IN SOUTH AFRICA

This section provides an overview of the most pertinent policy measures and legislation guiding ecological flow requirements studies in South Africa. This section provides a summary of the motivation for the National Water Act (No 36 of 1998). A more detailed summary of additional legislation that needs to be considered in any resource development is also highlighted in Appendix A.

### 2.1 THE NEED FOR NEW LEGISLATION

The law is never above the ruling values of the day and in a democracy the law should reflect the will and needs of the majority. The trigger event to the current national water policy was the change to a new government following the elections in 1994, which created a new political environment with a new mandate. Due to the fundamental political transformation from a minority regime to a democratic elected Government, the fairness of the country's entire legal system was called in question which included the law governing water.

The constitution is the supreme law of the land. In it are the fundamental legal principles, which must be upheld by the courts. These principles also control what the State and private persons may or may not do. The most pressing reason for a review of the South African water law was the overriding moral call to ensure that the law conforms to the new constitution. There are a number of sections in the constitution, which relates to water. Significantly, water is specifically referred to in the Bill of Rights chapter of the Constitution. Under the old water law these rights were difficult if not impossible to ensure. This was either because of the previous Government policy under apartheid or because of inadequacies of the old water law (DWAF, 1995).

The new Government was confronted with a situation where by a large section of South Africa's population had been excluded from land ownership and therefore denied access to water and the benefits that could be gained from it. South Africa's water law was in need of a thorough review for some time. This is supported by the experts and water resource managers (Thornton, 1989), which identified the need for strong supporting legislation for new concepts and insights.

There are several reasons why the water law needed to be revised (DWAF, 1995):

- The water law no longer reflected the needs in society such as the protection of rural people and nature conservation.
- The water law was outdated; it was based on antique systems and requirements of the previous century.
- The water law was primarily contained in the Water Act of 1956, but also scattered in 33 other Acts.
- The various principles of the old water law were derived from European countries, where the climate, culture and hydrology are very different to South Africa.
- There was a need for a well-structured water pricing system, which reflected the true value of water in South Africa.

- Very little consideration was given to customs and unwritten water and land laws of rural communities.
- The water law did not reflect the inter-relatedness of water sources and catchments.
- The definitions of terminology in the old Water Act was very technical and therefore difficult to understand and apply.
- South Africa was in the process of reform, which offered the opportunity to update legislation, which had been neglected previously.
- South Africa's international obligations in terms of shared rivers and catchments with neighbouring countries needed to be redefined to forge better relations and promote regional economic development (DWAF, 1997b).

In an address by the then Minister of Water Affairs and Forestry, Professor Kader Asmal, in 1998 he explained the need for new legislation and management practises as follows:

*“Our average annual rainfall is only slightly more than half the world average and projections indicate that our water demand could overtake water supply in some 25-30 years' time. Absolute shortages already occur in certain regions, which brought the need for various inter-basin transfer schemes; rainfall is unevenly distributed; extended and severe droughts regularly occur; and evaporation rates are high. These are the "givens". What we have to live with and adapt to. They are the vagaries of nature in this part of the world.”*

To these should be added to the impacts of socio-economic developments and considerations, such as:

- A massive backlog in water supply and sanitation services to previously disadvantaged communities, a legacy of a past that favoured the few and penalised the many.
- Serious pollution problems, deriving from point sources such as municipal and industrial wastewater treatment plants, but also from diffuse sources such as urban and agricultural runoff and defunct mines.
- Very little dilution capacity is available in our rivers and streams.
- Rapidly increasing demands on available water supplies due to industrial and agricultural development.
- Capacity building requirements, at all levels, to deal effectively with the water management requirements in the short and long term.
- Planning and construction of water resource projects designed to even out the wild variations in the water cycle.

**In summary: South Africa is a water-stressed country where water planners and managers are faced with increasingly complex issues and policy was needed to address these issues.**

## 2.2 RELEVANT SECTIONS IN THE NATIONAL WATER ACT 36 OF 1998 FROM AN ESTUARY PERSPECTIVE

### 2.2.1 LEGAL DEFINITIONS

S 1 (1) (ix): The expression “estuary” means a partially or fully enclosed body of water –

- which is open to the sea permanently or periodically; and
- within which sea water is diluted, to an extent that is measurable, with fresh water drained from land

#### **S 1(1) (xxvii): Water resource including estuaries**

Chapter 2: The Act prescribes a two-tier approach to the development of water resource management strategies, that is the national water resources strategy (“the NWRS”) and the catchment management strategy (“the CMS”). The NWRS sets out the macro-framework within which South African water resources must be managed. The NWRS is the ultimate responsibility of the (national) Minister of Water Affairs and Forestry. Catchment management agencies on the other hand, are responsible for the preparation of a CMS within their particular area of jurisdiction. The CMS allows for public participation by providing for the establishment of water management institutions (“WMIs”). Both the NWRS and the CMS incorporate the following concepts:

- ecological water requirements (the ecological reserve);
- social and economic requirements (including a reserve for basic human needs);
- the requirement for integrated resource management; and
- the “class” of the water body being managed (i.e. an integrated measure of quality).

### 2.2.2 DELEGATION OF POWER

The lead agent of this Act is the Department of Water Affairs. The Act is administered by both the head office as well as the regional offices in the provinces. Although the Act, for example, allows for uses listed under Schedule 1 of the Act, e.g. reasonable domestic use, small gardening irrigation and water in of animal and discharge of storm water, etc., this entitlement, however, does not override any other law, ordinance, by-law or regulation and is subject to any limitation or prohibition there under.

### 2.2.3 SPECIFIC PROVISIONS TO MITIGATE THREATS TO GOODS AND SERVICES PROVIDED BY ESTUARIES

#### *i. Modification of River flows:*

S 1(1) (xviii): The Reserve concept requires, amongst others, that the quantity of water that is required to protect aquatic ecosystems in order to secure ecological sustainable development and the use of the relevant water resource (including an estuary) be determined.

S18. The Minister, the Director-General, an organ of state and a water management institution must give effect to the Reserve as determined in terms of Chapter 2, Part 3 of this Act when exercising any power or performing any duty in terms of the Water Act.

S 21. The following are listed as water uses in the Act that may have an effect on river flow:

- Taking water from a water resource
- Storing water
- Impeding or diverting the flow of water
- Engaging in a stream flow reduction activity (S36)
- Engaging in a controlled activity (S37 and S38)
- Discharging water containing waste

S22. Water uses require a license with respect of where the water use:

- is permissible under Schedule 1 of the Act
- Is a continuation of an existing lawful use
- is permissible in terms of a general authorization (S39).

S41. A responsible authority, in terms of issuing licenses, may request from a license applicant to provide an assessment of the likely effect of the proposed license on the resource quality. A responsible authority may direct that any assessment must comply with the requirements contained in regulations made under S 26 of the Environmental Conservation Act 73 of 1989.

*ii. Pollution*

S 1(1) (xviii): The Reserve concept requires, amongst other requirements, that the quality of water that is required to protect aquatic ecosystems in order to secure ecological sustainable development and the use of the relevant water resource (including an estuary) be determined.

S18. The Minister, the Director-General, an organ of state and a water management institution must give effect to the Reserve as determined in terms of Chapter 2, Part 3 of this Act when exercising any power or performing any duty in terms of the Water Act.

S19. This section stipulates the conditions under which a person will be kept responsible for preventing pollution from occurring, continuing or recurring, as well as the remediation action to be undertaken.

S20. This section stipulates action to be taken when a water resource is polluted as a result of an emergency incident.

S 21. The following are listed as water uses in the Act that may have an effect on river flow:

- Discharging waste or water containing waste into a water resource through a pipe, canal, sewer or other conduct
- Disposing of waste in a manner which may detrimentally impact on a water resource
- Engaging in a controlled activity identified as such in S37 and S38
- Disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process.

S22. Water uses require a license, expect where the water use:

- is permissible under Schedule 1 of the Act

- Is a continuation of an existing lawful use
- is permissible in terms of a general authorization (S39).

S41. A responsible authority, in terms of issuing licenses, may request from a license applicant to provide an assessment of the likely effect of the proposed license on the resource quality. A responsible authority may direct that any assessment must comply with the requirements contained in regulations made under S 26 of the Environmental Conservation Act 73 of 1989.

*iii. Modification of Habitat*

S 21. The following are listed as water uses in the Act that may have an effect on river flow:

- Altering the bed, banks, course or characteristics of a water course
- Using water for recreational purposes.

S22. Water uses require a license, except where the water use:

- is permissible under Schedule 1 of the Act
- Is a continuation of an existing lawful use
- is permissible in terms of a general authorization (S39).

S41. A responsible authority, in terms of issuing licenses, may request from a license applicant to provide an assessment of the likely effect of the proposed license on the resource quality. A responsible authority may direct that any assessment must comply with the requirements contained in regulations made under S 26 of the Environmental Conservation Act 73 of 1989.

S110 (1). Before construction of any (government) waterworks, the Minister must, amongst other things prepare an EIA relating to the proposed water work which must, where the minister considers it appropriate, comply with the requirements contained in regulations made under S 26 of the Environmental Conservation Act 73 of 1989. These only fall in the net if commissioned by the government (Glazewski, 2000).

S1(1) (xxviii) A water work includes any borehole, structure, earthwork or equipment installed or used for or in connection with water use.

## 2.3 EFFECTIVENESS OF THE NATIONAL WATER ACT

The Water Act 36 of 1998 provides sufficient protection for estuaries in terms of:

- Flow modifications;
- Most water quality issues related to land-based sources; and
- Modification and destruction of habitat as far as it relates to water uses.

Problems encountered in terms of the above is mainly as a lack of:

- sufficient capacity to enforce (e.g. auditing of license stipulations) the Act;
- capacity to implement (e.g. functional CMAs not yet in place in many catchments, appropriate EIAs not being commissioned) the Act
- funding to conduct appropriate ecological flow requirement studies;
- environmental awareness in responsible authorities, e.g. in the CMAs;

- National estuary monitoring programme that focuses on both abiotic and biotic components to inform assessment and increase confidence;
- Strategic assessment tools (e.g. national desktop assessment) that recognises the regional connectivity between estuaries versus the current ad hoc approach.
- effective management and control of effluent disposal into estuaries, particularly with regard to smaller coastal towns, where overloading of waste water treatment work and malfunctioning septic tanks and conservancy tanks, subsequently into estuaries, is a regular occurrence during the holiday season. This is of particular concern in temporary open/closed systems.

However, the Water Act does not define marine waters as a water resource. As a result, the protection given to water resources such as estuaries does not apply to marine waters. The marine environment, however, often depends on inputs in terms of nutrients and sediments from rivers and estuaries, i.e. it also has a 'Reserve' for freshwater in terms of water quantity and quality (Lamberth et al., 2009). Furthermore, the marine environment and estuaries are strongly linked in terms of their ecological functioning, e.g. there are a number of estuarine species that have a marine phase in their life cycle. Therefore, if the state of the marine environment adjacent of estuaries deteriorates, the state of the estuary may deteriorate.

## 2.4 HYDRODYNAMIC REQUIREMENTS FOR ESTUARIES

In South Africa estuary EWR studies are conducted at four levels of assessment (ranked in order of increasing confidence), though only the last three of these have been officially used for estuaries:

- Desktop (method under development);
- Rapid;
- Intermediate; and
- Comprehensive.

A desktop assessment method is at present under development and only intended for use in strategic planning processes, e.g. National Water Resources Strategy or National Biodiversity (Conservation) planning processes only. Rapid determination is aimed at individual licensing of low volume allocations (small impact) in unstressed catchments, e.g. run-of-river abstraction of intermediate flows. Intermediate level assessments are intended for individual licensing of significant water resources development in relatively unstressed catchments, e.g. off-channel dam developments. In contrast comprehensive determinations are intended for all compulsory licensing and aimed at small or large impacts in very important and/or sensitive catchments. The degree of reversibility also plays a roll, e.g. a large dam development requires a high confidence assessment (i.e. comprehensive level) to ensure all ecosystem processes are accounted for.

Criteria for the selection of the level of an RDM determination include (DWAF, 1999):

- Degree to which the catchment is already utilised
- Sensitivity and importance of a catchment,
- Potential impact of proposed water use, and
- Availability of funding.

At all three levels of study the same fundamental information is required to identify the EWR to maintain a specific system in its desired condition. These include:

- Mouth State (*Can the estuary mouth close, and if so, under what flow conditions?*)
- Salinity structure (*What is the dominant salinity structure in the system and how do it respond to changes in flow?*)

These are the two fundamental questions that need to be addressed in any Estuary EWR study. To what degree they are resolved would depend on: the importance (ecological or socio-economic) of the estuary; its sensitivity to flow; and the degree of current, or proposed, flow modification.

The following chapters set out to highlight how to estimate the change in the above-mentioned questions.

### 3. HISTORICAL OVERVIEW

The history of ecological water requirements for estuaries in South Africa can be subdivided in to three parts, namely:

- Engineering approaches developed in the 1980s,
- Estuarine flow requirements refinement (1990s); and
- Development of the Resource direct measures (2000s).

#### 3.1 ENGINEERING APPROACHES DEVELOPED IN THE 1980S

In 1970 one of the first official allocations of freshwater to estuaries was done under the auspice of the Commission of Enquiry on Water Matters study (DWA, 1970) for “nature conservation” of estuaries and lake.

The concept of “environmental flows” – water allocated for ecological functioning – was first introduced in 1983 (Roberts, 1983). These initial attempts at quantifying estuary freshwater requirements were based on engineering principals with very limited understanding of biological consequences. In projections of future national water demand Roberts (1983) allowed for the requirements of estuaries, wetlands and conservation – estimates amounted to ~ 11% of the total estimated water requirements of all sectors by the year 2000. The first regional assessment was of South African estuarine freshwater requirements were developed by Jezewski and Roberts in 1986. Jezewski and Roberts (1986) used principles developed for the Tugela, Mgeni, Palmiet and Orange estuaries. (CSIR, 1980, 1984, 1983a and 1983b) to estimate the requirements of 145 estuaries in South Africa. These estimates considered two components:

- a flooding requirements; and
- an evaporative requirement.

Flooding was seen as the volume of water necessary to control the opening of an estuary mouth, flush out accumulated sediments and flood wetlands on the fringes of the estuaries. It was defined as a 2-year return period flood. The flooding volume was determined from a triangular hydrograph with a peak flow equal to the 2 year flood, a rising limb with a duration equal to the time of concentration and the receding limb duration twice this period for catchments > 500 km. For smaller catchments the receding limb was estimated as equal to the rising limb.

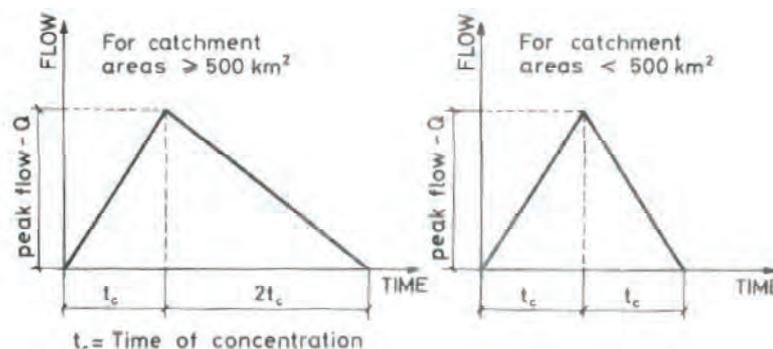


Figure 3-1 Simplified hydrographs of the 2 year flood indicating the differences between a large and small catchments (Source: Jezewski and Roberts, 1986).

The evaporative requirement was seen as the amount of water needed to compensate for evaporative losses and prevent hyper salinity (> 35 PSU). Calculations were based on the mean annual net evaporations from the open water surface area together with its associated wetlands. Estimations of the flooding requirements were nearly four times that of the evaporative requirement and were considered less accurate (Morant and Quinn, 1996). Generally Jezewski and Roberts (1986) found that less than 5% of the Natural MAR was needed to ensure ecological functioning.

DWA (1986) refined the Jezewski and Roberts (1986) estimates from being just an annual allocation of freshwater to estuaries. According to DWA (1986) the total freshwater requirements of estuaries and lakes amounted to 5% of natural MAR and was estimated to represent as much as 15% of the utilisable resources. The total amount of water required for environmental management of estuaries in South Africa (including conservation needs) was estimated at  $2\,954 \times 10^6 \text{ m}^3$  per year by 2000. This amounted to 13% of total demand.

This is also the first time that the Department of Water Affairs recognised estuaries as a valid user. This document also represents one of the first official communications that states that not all estuaries are equally important as some systems seem to have “little ecological value” and enjoy low priority when water is scarce. This view point highlighted the concept of a “workhorse estuary” that can be “sacrificed” to meet growing demands. DWA (1986) stresses that it may not be possible to meet the environmental water requirement of each estuary and that benefits would have to be weighed carefully against water use in each case.

These initial estimates are all significantly lower than those estimated by more recent detailed and holistic analyses incorporating aspects of the biological functioning of the estuaries. These estimates did not take into account biotic-abiotic relationships within estuaries focussing instead mostly on flooding and evaporation.

These studies did not provide detail on seasonal or monthly distribution of the recommended allocations. These earlier estimates were based on simplistic models and the quantitative results were presented as first-order attempts to indicate the probable freshwater demand of estuaries for water resources planning. While these first estimates were developed in the recognition of the water requirement of the environment, they were not intended as ecological water requirements. Unfortunately some major dams, e.g. Mpufu on the Kromme, were constructed under these guidelines leading to this system losing its salinity gradient, becoming freshwater starved and virtually an arm of the sea.

### 3.2 FIRST ESTUARINE FLOW REQUIREMENTS (EFR) STUDIES IN SOUTH AFRICA

In the 1990s the Department of Water Affairs reaffirmed its commitment to establishing the water requirements of estuaries and commissioned a number of studies to more accurately determine freshwater requirements of South Africa’s estuaries. The principal approach in these earlier studies was to convene a workshop of interested parties and estuarine specialists. Through a discussion of issues, participants would aim to converge on a preliminary estimate of the freshwater requirements and to provide in this respect recommendations (Morant and Quin, 1999).

Key considerations in these early EFR studies were:

- 1) seasonal mouth conditions;
- 2) regular flushing (defined as resetting of salinity profile);

- 3) maintenance of nursery function; and
- 4) socio-economic consideration (e.g. algal blooms or recreation).

Flow estimates were provided as an annual volume. Study confidences were captured as well as further data requirements (defined as baseline surveys and monitoring needs).

These earlier EFR studies (e.g. Great Brak, Swartkops, Olifants, Palmiet, Mkomazi) set the scene for the current approach to Ecological Flow Requirements. Many of the approaches developed to quantify the estuaries responses to flow were conceptualise in these earlier studies.

Of all the work conducted in the 1990s the Great Brak EFR was the most seminal, setting the standard for future studies in a number of aspects (CSIR, 1990). Key features of the Great Brak EFR included:

- The study included the evaluation of hydrodynamic, sediment processes and water quality (e.g. nutrients, oxygen, turbidity).
- This study was one of the first studies to have ecological components form part of the assessment process, i.e. vegetation and invertebrates.
- Salinity distribution was modelled using a 1-dimension numerical model based on the mathematical principals incorporated in the DHI Mike 11 commercial modelling package.
- It was the first study in which the scenario approach was actively used to evaluate environmental responses to flow. Monthly flows scenarios for a 64-year period were simulated for natural, pre-Wolvedans dam, and post Wolvedans-dam configurations using state of the art hydrological models.
- As part of the hydrodynamic component mouth state was linked to river inflow to allow water resource managers hands-on management of mouth state after the construction of the dam.
- It had a detailed long-term environmental monitoring programme (e.g. mouth conditions, river flow, water levels, water quality, vegetation, invertebrates) to guide refinement of the initial findings.
- The EFR study included a socio-economic assessment to determine local socio needs and incorporate these identified requirements in flow allocations (e.g. open mouth conditions for recreation, flushing of nuisance algal blooms).
- This study also advocated an “adaptive management” approach, which acknowledged that not all aspects will be known in the initial EFR study and that the operational management rules and, in theory, the initial EFR will need to be adapted as new information becomes available. Therefore the project followed the “20:80 rule” in which it was conceded that for 20% of the effort about 80% of information can be generated.

Not all earlier EWR studies were as complex as the Great Brak study, but in the decade 1990-2000 incremental refinements were continuously being implemented with consecutive studies. For example, numerical modelling was used to predict salinity penetration in permanently open estuaries – Mike11 one-dimensional modelling applied on the Swartkops, Keurbooms EWR studies.

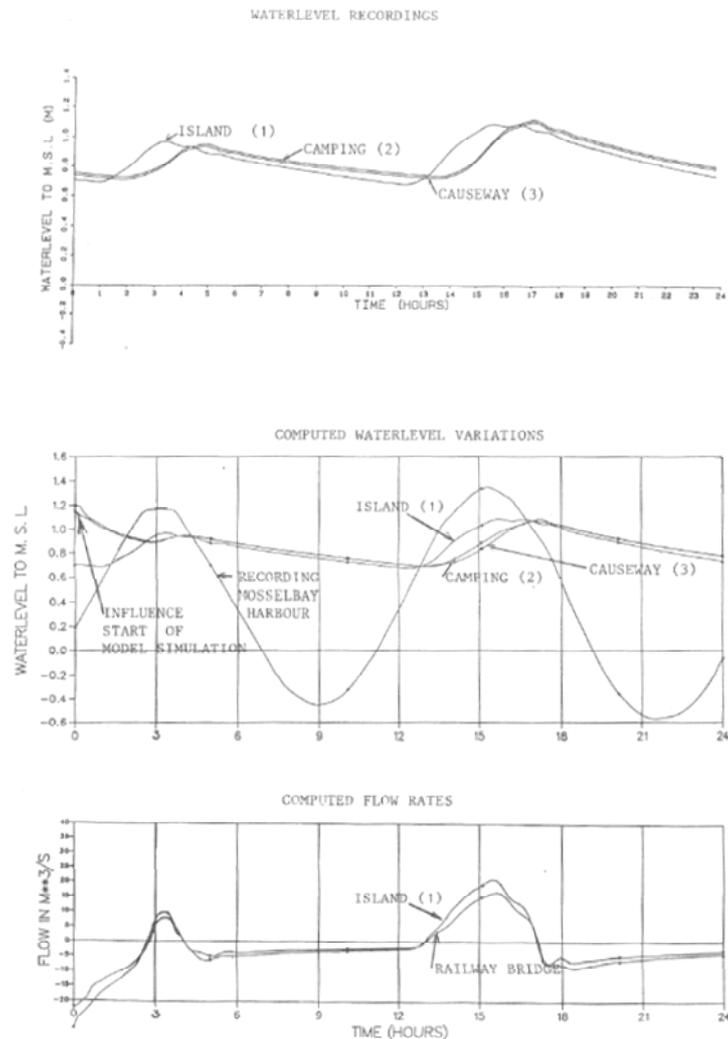


Figure 3-2 Simulated water levels and tidal exchange data generated for Great Brak Estuary EFR study in 1990 (CSIR, 1990)

The addition of fish and birds as an essential component of the ecology was done as part of the Swartkops, Olifants and Berg EWRs. The refinement of the linking of hydrodynamic and water quality parameters to flow ranges, in short the development of Abiotic state concept, was first formally done in the in Palmiet EWR (1998). The Nhlabane EWR highlighted the value of water level data and mouth condition data collected for the correlation of mouth state to various flow ranges. While these later ecological water requirement studies highlighted the need for considerable higher freshwater allocations to estuaries, they still suffered from being consensus based representing an intuitive expert assessment rather than a scientific defensible method (Morant and Quinn, 1999). They were also aimed at estimating annual total flow allocations, with limited detail on seasonal and monthly distribution. The lack of monitoring data also hampered the “firm up” of initial estimates and the refinement of specialists understanding.

With the proclamation of the NWA it became imperative that the methods for flow requirement determination be formulised and standardised to allow a scientific defensible and repeatable result.

## 4. INTERNATIONAL EWR APPROACHES APPLIED TO ESTUARIES

As indicated before, three main countries have developed environmental flow assessment methods for estuaries i.e. South Africa, Australia and the USA. Most of these methods were developed to provide solutions to real world problems, i.e. required a practical approach. The majority of methods are data rich and emphasize long-term monitoring so that the impacts of freshwater inflow alteration can be understood.

This section sets out to briefly review international approaches to ecological flow requirements methods, with an emphasis on estuarine EWR requirements.

Using Alber (2002) as starting point, most EWR methods can be classified as one of four types of approaches:

- Methods that use hydrology-hydrodynamics as a proxy for change in the ecosystem;
- Resource based approaches (aimed at both the use of living and non-living features);
- Methods that view the ecosystem as the end-point; or
- A hybrid of the above mentioned.

### 4.1 HYDROLOGY-HYDRODYNAMICS AS A PROXY FOR ECOSYSTEM CHANGE

Methods that focus on evaluating change in hydrology or hydrodynamics as a proxy for change include inflow-based methods that establish inflow requirements relative to how much freshwater inflow can be deviated from, e.g. Percent-of-flow approach and Indicators of Hydrologic Alteration (IHA) (Flannery et al., 2002; Alber and Flory, 2002, Alber (2002)).

For example, the Texas Optimisation Approach used a series of relationships between historic monthly inflow and the catch data of fish, crustaceans and mollusks (Matsumoto et al., 1994 cited in Alber, 2002). These relationships were then used to build the Texas Estuarine Mathematical Programming model (TxEMP) (Matsumoto et al., 1994; Powell and Matsumoto, 1994; Powell et al., 2002). TxEMP modelled salinity-inflow and inflow fishery harvest relationships in order to optimize inflow-harvest relationships. This method was applied to all estuaries in Texas (Montagna et al., 2002).

### 4.2 RESOURCE BASED APPROACHES

Resource based methods aim at sustaining particular resource uses (e.g. fishing, recreation, tourism) within the river or estuary and freshwater inflow requirements are determined according to the amount required by these resources, e.g. Texas Optimisation Approach, Valued Ecosystem Component or Target habitats methods; and Determining flows for fisheries production (Montagna et al., 2002; Matsumoto et al., 1994; Powell and Matsumoto, 1994; Powell et al., 2002; Doering et al., 2002; Mattson, 2002; Halliday et al., 2003; Robins et al., 2005, Lamberth et al., 2009).

A good example of this type of approach is the framework developed in Australia for the allocation of freshwater for fisheries production (Halliday et al., 2003; Robins et al., 2005). Fisheries production and status of fish stocks is used here as a proxy for ecosystem health. The framework is based on the

concept of Gippel (2002) who suggested that key flow events may trigger or support key ecological processes and that these flow events should be linked to specific biological processes or life cycles of estuarine organisms. Robins et al. (2005) used correlative analyses in the Fitzroy River Estuary to relate catch to flow and rainfall variables.

### 4.3 ECOSYSTEM BASED APPROACH

Ecosystem based approach is typified by approaches in which a selection of living and non-living components are evaluated to establish the degree of change in the ecosystem. These approaches to EWR assessments tend to be more holistic. Methods that see the ecosystem as the Condition based methods establish inflows relative to what condition the estuary is aimed to be maintained in and the amount of freshwater required for that level of maintenance, e.g. X<sub>2</sub> approach (Kimmerer, 2002; Alber, 2002). Adams (in prep) also contest that more recent environmental flow assessments for estuaries take a more holistic ecosystems based position, with examples of methods or approaches including: Resource Directed Measures, National River Health Program, FLOWS, Benchmarking and ELOHA (Ecological Limits of Hydrological Alteration), Risk Assessment, BAFFLER (Bayesian Adaptive Framework for Flows to Maintain Estuarine Resources), Estuary Flows Map, Simple Estuarine Response Model (SERM) (Adams et al., 2003; Pierson et al., 2002; Peirson et al., 1999; Peirson et al., 2001; Bishop et al., 2001; Cox and Peirson, 2003; Peirson and Church, 2003; Bishop, 2005; Boyes, 2006; Hardie et al., 2006; Sherwood, 1983; Sherwood, 1985; Sherwood et al., 2003; Brizga et al., 2002; Schofield et al., 2003; Close, 2005, 2007; Gippel et al., 2009; Baird et al., 2001).

Pierson et al. (1999, 2001, 2002) developed the recommended method for Australia as part of the National River Health Program. The method comprise a 10 step multi-disciplinary, adaptive management approach that provides a check list of major ecological processes affected by flow to estuaries and assesses the risk associated with reduced flows. Numerical modelling is used to indicate the changes in longitudinal distribution of salinity in response to freshwater inflows and climatic conditions. These results were then used to assess the effect of changes in salinity on the representative biota and the degree of risk to selected biota.

### 4.4 HYBRID APPROACHES

Hybrid approaches to environmental flows tend to be very pragmatic with an element of Risk Assessment attached to it. The best example of this is the Pierson et al. (2002) method that first assesses the risk flow modification holds for the ecosystem before embarking on a full ecosystems assessment.

### 4.5 DISCUSSION

Proxy approach in which change in the hydrology or hydrodynamics (e.g. indicator salinity) serves as a proxy for condition change. A key assumption is that all ecosystem change is linear and that only flows drive health. Accumulative pressures do not form part of this framework. This type of approach do not allow for the synergistic effects of multiple pressures to be evaluated, e.g. a decrease in flow and an increase in fishing pressures due to increased development. In addition, percentage flow or statistical approaches tend to disregard statistical outliers (e.g. less than 10% of average inflow or exceedance of 90 percentile of flow) as they are of low incidence. Unfortunately, in the case of an estuary drought and floods are the very forces that determine the envelope in which the system operates and in not addressing this as part of the flow assessment key ecosystem processes may be overlooked.

Resource Based approach in which the conditions of a specific species or resource serves as a proxy for acceptable change may show some sensitivity to nonlinear responses, e.g. in addition to flow the impact of fishing effort may also feature. Habitat and pollution pressures are often disregarded in this type of study. Generally only one or two of a suite of ecosystem services are evaluate to estimate the possible degree of change an ecosystem may experience and health is reported in this context. This type of approaches also have a very limited ability to project future trajectories of change, especially if feedback loops are through non-linear processes, such as sediment movement that is normally event scale and not continuous.

Ecosystem based approaches are more holistic, but data intensive and require some reduction in complexity. Studies vary in their selection of parameters that needs to be evaluated and the timeline that change are reported on. In highly modified system it is nearly impossible to hind-cast to natural states and health improvements or degradation is reports in terms of improved ecosystem services.

A number of methods follow a hybrid approach with a pre-feasibility /risk assessment component that first evaluated the degree to which flow will be altered or the hydrodynamics be affected. If this is judged to be significant a detailed full scale investigation of all components will be under taken. Although there is value in this approach to study resource allocation, it hinges on the perception of the physical specialists and /or ecologist regarding the degree of ecosystem shift to be expected. In the South African context this risk assessment component is not pursued as most estuaries are either sensitive to flow modification or already water stresses.

## 5. PHYSICAL PROCESSES AT PLAY IN AN ESTUARY

This section provides a brief overview of the driving forces of estuarine hydrodynamics.

### 5.1 ESTUARINE CLASSIFICATION BASED ON HYDRODYNAMICS FEATURES

While variations in climate, topography and catchment geology give rise to a wide variety of estuarine types in South Africa, from a hydrodynamics perspective all estuaries in South Africa's fall in one of two categories, namely permanently open or temporarily open/closed estuaries. Estuarine bays, estuarine lakes and estuarine river mouths are all sub-classes of the above stated estuarine types from an abiotic process point of view.

- **Permanently open estuaries:** Only about 30% of South Africa's nearly 300 estuaries are permanently open to the sea (Whitfield, 1998, Van Niekerk and Turpie, 2011). These permanently open estuaries normally have large catchments and relatively high runoff throughout the year. Vertical and horizontal salinity gradients are present and are modified by the river inflow and mouth condition. Hypersaline conditions can occur in the upper reaches during times of severe drought. Tidal and fluvial mixing is the main drivers of abiotic processes in this type of estuary. During low flow conditions the mouths of this type of estuary can become very constricted (reducing tidal flushing), but it would never close. Examples of permanently open estuaries are the Mtamvuna and Olifants estuaries.
- **Temporarily open/closed estuaries:** The remaining 70% of South Africa's estuaries are temporarily open/closed systems (Whitfield, 1998). This means that they are isolated from the sea by the formation of a sand berm across the mouth during periods of low or no river inflow. Such estuaries stay closed until their basins fill up and their berms are breached by increased river flow. Mouth breaching normally results in the removal of significant amounts of sediment. However, infilling from marine and fluvial sediment can be rapid varying from a few days to months (Perissonotto et al., 2004 and Van Niekerk et al., 2080). Hypersaline conditions occur in these estuaries during times of drought due to evaporative losses. Tidal and riverine inputs control the mixing processes in these systems when the mouth is open, while wind mixing becomes the dominant process during extended closures. Examples include the Mngazi and Mhlanga estuaries.

### 5.2 ESTUARINE RESPONSE OF TO MODIFICATION IN RIVER INFLOW

#### 5.2.1 PERMANENTLY OPEN ESTUARIES

Permanently open estuary's mouths are not sensitive to flow reduction. This is either because the runoff and tidal flows are high enough to maintain open mouth conditions throughout the year, even during drought years, or because of mitigation factors such as mouth protection.

In the case of permanently open estuaries changes in runoff, cause changes in the extent of saline penetration into the estuary. The more the runoff decreases, the further the extent of saline penetration. This in turn reduces the brackish and freshwater mixing zones in the estuary, i.e. reduces the estuarine habitat. Further reduction in stream flow can result in the complete elimination of this mixed zone so that, effectively, the system functionally becomes an arm of the sea, e.g. Kromme

Estuary. If there is no inflow at all a reverse salinity gradient may develop where the salinity at the head of the estuary may exceed that of seawater, e.g. Kariega where 41psu has been recorded at the head.

Permanently open estuaries normally have large catchments and relatively high runoff throughout the year, which makes them a target for extensive stream flow reduction activities in the form of irrigation and also of major dam developments and large abstraction schemes. The extent of stream flow reduction in South Africa varies from nearly 100% (e.g. Kromme) to about 5% (e.g. Keurbooms) in permanently open systems.

Changes in salinity structure are seen as the major driver of ecosystem change. In low confidence studies especially salinity is used a proxy for a host of processes and variables, e.g. reduced flushing, increased retention, loss of pelagic habitat, loss of production.

The variation in salinity distribution gradients in permanently open estuaries and the sensitivity to flow changes in this regard, is very difficult to quantify unless numerical modelling is undertaken (See Section 8 for more detail). In general if an estuary is permanently open, its sensitivity to **reduction in seasonal base flows during the low flow period** is assumed to be **very high** and, therefore a reduction in river inflow during the low flow period should not be considered. Permanently open estuaries are often less sensitive to reductions in higher flows, e.g. flow band 50-100 m<sup>3</sup>/s.

### 5.2.2 TEMPORARILY OPEN/CLOSED ESTUARIES

Temporarily open and closed estuaries, as the name implies, exhibit changes in the duration of mouth closure, and related changes in the salinity penetration, due to flow manipulations.

Temporarily open/closed systems are very sensitive to stream flow reduction, i.e. a small change in the runoff can extend the period of mouth closure from two months to five months in the low flow period, e.g. Klein Estuary in Western Cape. In extreme cases, fresh water reduction can cause almost permanent mouth closure, e.g. Isipingo Estuary.

Reduction in stream flow may lead, paradoxically, to a reduction in salinity in a small system. Reduction in inflow can lead to mouth closure and, provided the inflow exceeds evaporation and seepage losses, a progressive freshening of the lagoon until such time as rising water levels lead to a breaching of the berm closing the mouth, e.g. Bot and Groot Brak. The impact can be an almost complete loss of the estuarine biota and its replacement with freshwater species.

Typically, the mouth of an estuary is classified as either 'open' or 'closed'. However, research conducted in the past five years by the CSIR on small systems highlighted the existence of a third mouth state (Taljaard *et al.*, 1997; Huizinga *et al.*, 1998; Huizinga & van Niekerk, 1998; Huizinga *et al.*, 2000; Huizinga *et al.*, 2001). It has been observed that an estuary mouth can also be in a semi-closed state (Van Niekerk *et al.*, 2002). In the semi-closed state, the mouth of an estuary is nearly closed with only a shallow, narrow opening allowing water to "trickle" out to sea, but the mouth is then too perched and shallow for tidal exchange. However, seawater may still enter the estuary during spring high tides allowing some brackish, estuarine environment to persist.

A semi-closed mouth state is a phenomenon characteristic of many smaller estuarine systems along the South African coastline, for example the Palmiet, Nlabane, Mdloti, Mngazi and Lourens estuaries. In the past, the existence of this semi-closed state was not recognized and therefore not seen as relevant to the ecology. The migration of juvenile fish or invertebrates can sometimes still occur

through such a restricted mouth even if tidal influence is negligible. Reductions in river flow can affect the natural variation in the state of an estuary mouth, and subsequently the ecological character. For example, a small change in river inflow could change the mouth of an estuary from a semi-closed mouth to a closed mouth with its related impact on the ecology. The semi-closed mouth state should not be confused with overwash by big waves during storm events or during spring tides, which only occur for short periods or under extreme conditions.

### 5.3 SENSITIVITY TO FLOW REDUCTION

The resultant of the high energy coastline (i.e. significant closing forces) and generally low runoff (limited opening forces) is that South Africa's nearly 300 estuaries display a high sensitivity to changes in runoff.

In evaluating the sensitivity of individual estuaries to flow reduction both the forces that potential could close an estuary mouth and the forces that assist in maintaining open mouth conditions need to be evaluated.

The major forces that maintain open mouth conditions are:

- River inflow; and
- Tidal flows

The major closing forces along the South African coastline are:

- Wave energy, of with the following factors are co-variants (and interactive) and determine the degree of wave energy at a mouth area:
  - beach slope;
  - median grain size;
  - berm height; and
  - width of the breaker zone.
- Sediment availability (both marine and catchment).

#### 5.3.1 OPENING FORCES (MAINTAIN OPEN MOUTH CONDITIONS)

**River inflow is the major driving force** that maintains open mouth conditions in South African estuaries. **In small estuaries it is the only driving force** that maintains open mouth conditions. In larger system, **tidal flows assist in maintaining open inlets**, for example, tidal flows alone are keeping the mouth of the Kromme Estuary mouth open.

In general, estuaries larger than about ~100 ha can maintain a permanently open mouth condition. Medium size estuaries (<100 ha) can sometimes maintain open mouth conditions over spring tides and close over neap tides when tidal flows are at its least, e.g. Great Brak and Seekoei Estuary.

### 5.3.2 CLOSING FORCES

The major closing forces are the wave energy **at the mouth of the estuary** and the **available sediment** that is being carried into the system.

To assist in assessment of wave energy at a mouth the following co-variants can be assessed:

- *Breaker zone width*: The width of the breaker zone gives an indication of the available wave energy at the estuary mouth, i.e. the potential energy available to carry a suspended sediment load into the estuary. A narrow breaker zone usually indicate more energy availability for sediment transport near or at the mouth and a wide breaker zone indicates that most of the energy is dissipated in the surfzone and there is potentially less energy for sediment transport into the mouth.
- *Beach slope*: A steep beach slope (in the surfzone area) normally means that high-energy wave conditions occur on the beach at the mouth, resulting in higher suspended sediment loads that can enter the estuary. This type of beach slope is characteristic of the KwaZulu-Natal coastline. The beach slope can also vary significantly due to erosive storms vs. long periods of relative calm seas. Generally the steeper the slope of a beach, the higher the wave energy, the greater the possibility of sensitivity to mouth closure. A mild beach slope means that the majority of your wave action occurs in the breaker zone further from the shoreline and there is less likely hood of sediment being transported into the estuary mouth.
- *Medium grain size*: Coarse grain size sediment on the beach, adjacent to an estuary mouth, in general indicates the that there is potentially significant energy available for sediment transport, while finer grain sediment indicate a more gentle wave energy and therefore less ability to transport sediment into the mouth area.
- *Berm height*: High sand berms >3.0 m MSL indicate significant wave energy available to transport sediment into an estuary mouth, while lower sand berms (<3.0 m MSL) are associated with less potential wave energy to transport sediment into an estuary.

**Sediment availability** is the other major contributing closing factor for estuary mouths in South Africa. Sediment availability is influenced by the longshore transport, sediment from the catchment and the resident sediment available in the mouth region of an estuary.

- *Longshore sediment transport*: The longshore sediment transport rate in the marine environment indicates the potential amount of sediment available for mouth closure. Not all of this sediment will reach the estuary mouth. If the transport is occurring in close proximity of the estuary mouth, it indicates that more sediment is available for transport into the mouth. Whereas if the longshore current is deflected, for example by a rocky headland, less sediment is available for downdrift of the headland transport by wave action into the estuary mouth (e.g. Nahoon Estuary).
- *Catchment sediments*: Catchment sediments can also contribute to mouth closure, especially in section of the coast where less marine sediment is available. Catchment sediment can accumulate outside the mouth of an estuary after a major flood event and be transported into the mouth under high wave conditions (e.g. Orange) or gradually accumulate in an estuary mouth and cause closure (e.g. potentially at Lupatana Estuary).

- *Resident sediment*: The size and width of the beach at the estuary mouth also gives an indication of the sediment availability for mouth closure. A predominantly rocky coastline with widely dispersed pocket beaches has significantly less sediment available for mouth closure than long stretches of wide beaches.

**Mitigating factors** that assist in prolonging open mouth conditions in medium to small size estuaries include: **degree of mouth protection** (e.g. rocky headland or reefs in the surfzone) and **sub-tidal mouth protection below the water surface** (e.g. Rocky shelf running below the surface in the sea that spills wave energy).

**Factors that contribute to mouth closure** include structures that inhibit river or tidal flows such as sand ripples in Keurbooms Estuary (natural bed forms) or the causeway across the Seekoei Estuary (artificial).

**It is important to recognize that each estuary is unique in terms of the nature of the various factors that influences its hydrodynamics or sensitivity to flow, such as bathymetry, runoff, degree of mouth protection.** For example, two estuaries could occur adjacent to one another, but completely different processes could be responsible for maintaining an open mouth due to differences in local coastal conditions, e.g. limited mouth protection (e.g. Mngazi) or rocky headlands (e.g. Mngazana).

## 6. WATER LEVELS

### 6.1 TIDAL AMPLITUDES AND BERM HEIGHTS

South Africa's coast is generally characterised by low tidal ranges and high wave energy, making it a wave-dominated coast (Cooper, 2001). Therefore the approximately 300 functional estuaries are predominantly micro-tidal systems (tidal range < 2 m) and they are highly dynamic and shallow (average depth of 2-3 m).

Owing to strong wave action and high sediment availability, more than 90% of the estuaries have restricted inlets, with more than 75% closing for varying periods of time when a sand bar forms across the mouth (Whitfield, 1992). The higher the degree of wave energy at the mouth, the more constricted the mouth will be. There is therefore a continuum in the degree of mouth constriction, varying from wide open (e.g. Knysna), open (e.g. Olifants), constricted (e.g. Great Brak) to perched (e.g. iZosha). In very high energy coastal environments the estuary mouth becomes perched on the berm. Perched estuaries tend to have the most restricted mouths with limited tidal range due to their elevation relative to sea level (Figure 5.7). An additional feature is that small perched estuaries tend to drain between 30-70% of their water under open mouth conditions, i.e. they have more water column habitat when closed than open. While larger temporarily open/closed estuaries tend to be more productive under open mouth conditions, perched estuaries also tend to be more productive (and better nurseries) during the closed phase (Perissonotto *et al.*, 2004).

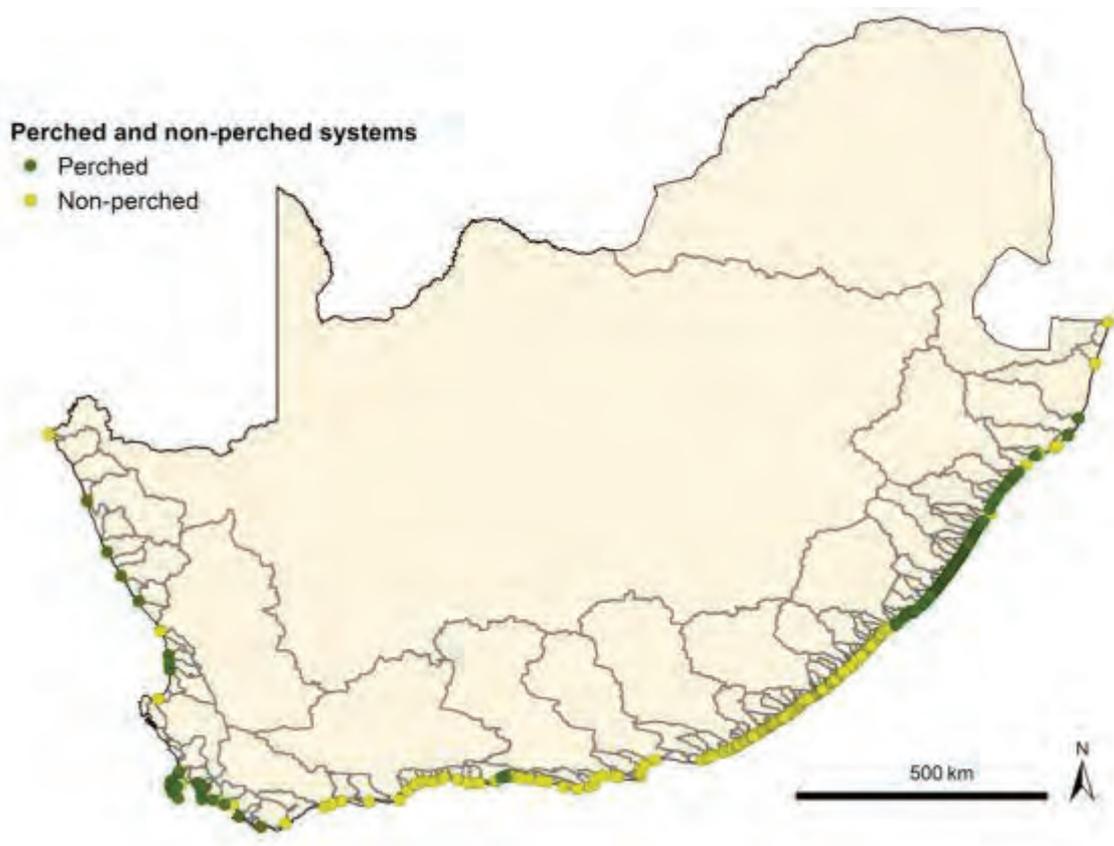


Figure 6-1. Mouth position on berm (perched, non-perched) in South Africa's estuaries (Modified from Cooper, 2001).

Cooper (2001) generalized the wave energy and sediment availability along the coast of South Africa, indicating that most of the estuaries along the west coast and KZN coastline are perched.

More information is required to disaggregate these general features in a meaningful manner. Nevertheless the following generalization can be made from measured data along the coast: in permanently open estuaries the tidal range at springtide is normally greater than 1.5 m (e.g. Berg, Olifants, Sundays), between 1.5-0.5 m for a large temporarily open estuary (Groot Brak, Seekoei); and between 0.5 to 0.2 m for a perched or small temporarily open estuary (e.g. Buffels, Lourens, East Kleinemonde, Little Amanzimtoti). All estuaries become more constricted during the low flow season (the exceptions are Knysna and Mhlatuze) and tend to be more open to the sea during the rainy season.

As a general reference Cooper (2001) can be taken as indicative of average berm heights along the South African coastline. The West Coast and KwaZulu-Natal regions generally display berm heights greater than 3.5 m MSL (along a exposed coastline with adequate sediment supply), while sand berms along the southern part of the South African coastline tend to be lower (between 3.0 to 2.5 m MSL). As indicated before the degree of mouth exposure, available sediment supply (coastal and catchment) and runoff (indicative of breaching frequencies) determine the extent to which individual estuary berm heights differ from this generalisation.

Where possible measured data is used to estimate berm heights, but unfortunately data is only available for about 10% of all South African estuaries. For rapid level EWR assessment the general berm conditions highlighted above are used as input to flow requirement estimates, while for comprehensive level studies modelling can be undertaken.

## 6.2 PROPOSED METHOD FOR ESTIMATING BERM DEVELOPMENT

Besides being related to wave conditions, sediment characteristics and, to a lesser extent, aeolian (wind) transport, the formation and dimensions of the berm also affect the mouth state, wave overwash and seepage. Two separate methods were employed to estimate the value for the berm crest height ( $B_c$ ). The first is derived from Swart (1974) and the second from Nielsen and Hanslow (1991) (Theron and Bergman, 2007).

Swart (1974) used a laboratory test to derive a method that determines the “D-profile limits” for a beach. These extremities were defined to be the upper and lower limits that wave action causes sediment transport and hence affects the developing profile of a beach. This estimate makes use of the Significant Waveheight ( $H_s$ ), the Wave Period ( $T$ ), the average grain size of the sediment making up the Berm ( $d_{50}$ ). The assumption is made that the upper D-profile limit is related to the berm crest elevation, and we therefore made the berm crest height in a particular simulation in this study equal to the highest value of the upper D-profile limit calculated up to that time.

Using this method, the berm crest height ( $B_c$ ) is expressed as follows:

$$B_c = d_{50} \cdot (7644 - 7706e^{-A})$$

where: 
$$A = \frac{0.000143 \cdot H_s^{0.488} \cdot T^{0.93}}{1000 \cdot d50^{0.786}}$$

and  $d50 = 2.99 \times 10^{-4}$  m, which is an average value for the sediment at Groot Brak.

The Nielsen and Hanslow (1991) method makes use of gravitation acceleration ( $g=9.81 \text{ m.s}^{-1}$ ),  $H_s$ ,  $T$ , and the tangent of the beach slope ( $\tan(\alpha)$ ) to calculate the height to which a wave would travel up the beach slope. This height was termed the “wave run-up height”. The present method uses the assumption that the wave run-up height is the highest level to which the waves have an effect on sediment transport, and therefore the berm crest height in a particular simulation would be equal to the highest wave run-up height experienced up to that time. Two different formulae are derived for the berm crest height using this method, depending on whether  $\tan(\alpha)$  is greater or less than 0.1

For  $\tan(\alpha)$  greater than 0.1:

$$B_c = WL + 0.83 + 0.6 \cdot \tan(\alpha) \cdot \sqrt{\beta}$$

And for  $\tan(\alpha)$  less than or equal to 0.1:

$$B_c = WL + 0.83 + 0.05 \cdot \sqrt{\beta}$$

Where:

$$\beta = \frac{H_s}{\sqrt{2}} \cdot \frac{gT^2}{2\pi}$$

and  $g$  is the acceleration due to gravity (equal to  $9.81 \text{ m.s}^{-1}$ ).

Tidal water levels in the sea vary around the mean sea level (MSL). When calculating  $B_c$ , the value for  $WL$ , which represents the water level of the ocean, was taken to be related to MSL. For example the typical value  $\tan(\alpha)$  at the adjacent beach at Groot Brak is 0.071.

Both the Swart and Nielsen & Hanslow berm models are sensitive to the incident wave conditions (these being the main drivers for berm dynamics). The berm crest height as calculated by the Swart method is very sensitive to the value for  $d50$ , while the Nielsen & Hanslow model is sensitive to beach slope and water level. As beach slope and grain size are strongly correlated (e.g. Wiegel, 197) the two methods can be considered consistent in this aspect. In practise, it is easier to obtain grain size data than beach slope. Beach slopes are also typically more variable in time the grain size. Thus, it is generally be easier to obtain input for the Swart model.

## 7. MOUTH STATE

**Problem:** More than 70% of South Africa's estuaries have closed mouth conditions from time to time. Less than 10% have some continuous gauging of the mouth state and less than a third have some observational data regarding the mouth state.

**Response:** Development of robust method(s) for mouth state predictions in a data poor environment that can be applied at various levels of EWR assessment.

Usually temporarily open estuaries will remain closed until their water basins fills up to a level equal to the height of the sand berm across its mouth. Any additional water added to the estuary basin after this will cause a mouth breaching (assuming that inflow exceeds the outflow from the estuary). The foremost assumption in the development of a water balance model is therefore that a breaching will occur when the Water Level (WL) in the estuary basin equals, or is greater than the height of the berm ( $B_c$ ). This results in the algebraic inequality which states that a breach occurs if:

$$WL(t) \geq B_c(t)$$

The most accurate way of determining the mouth conditions of an estuary is through analysing measured data in conjunction with flow inputs. Both continuous water level recording data from a station near the mouth of the system and/or a daily observational record has proven numerous times to be the most effective approach to quantifying the open mouth state. In the absence of data, numerical approaches can be used to estimate the degree to which an estuary mouth is open, but this will always just be a model of the real world connectivity between the catchment and the sea.

### 7.1 BALANCE OF WATER VOLUME IN A CLOSED ESTUARY

The volume of water in an estuary at a particular time  $t$  can be described as the sum of the various volumes entering and/or leaving the system by different means, as well as the previous volume of water in the estuary (i.e. at time  $t-1$ ). This procedure which accounts for quantity of water in an estuary is known as the Water Volume Balance (e.g. Smakhtin, 2004).

Potentially flows that enter an estuary include: the inflow from the river,  $V_{inflow}$ ; Precipitation directly onto or from the estuary's surface ( $V_{precip}$ ); the volume of water that enters the estuary over the berm through wave action ( $V_{overwash}$ ); the volume of water entering through anthropogenic influences ( $V_{artificial}$ ); and the volume of water directly entering through the ground ( $V_{ground}$ ). Potentially outflows from the estuary: Evaporation from the estuary's surface ( $V_{evap}$ ); the volume of water that seeps through the berm ( $V_{seepage}$ ); the volume of water exiting through anthropogenic influences ( $V_{artificial}$ ); and the volume of water exiting through the ground ( $V_{ground}$ ). Figure 7-1 provides a graphic representation of the water volume balance in a closed estuary.

The equation for the **Volume of water** in the estuary at time  $t$ , is thus given as:

$$V_t = V_{t-1} + V_{inflow} + V_{precip} + V_{evap} + V_{seepage} + V_{overwash} + V_{artificial} + V_{ground}$$

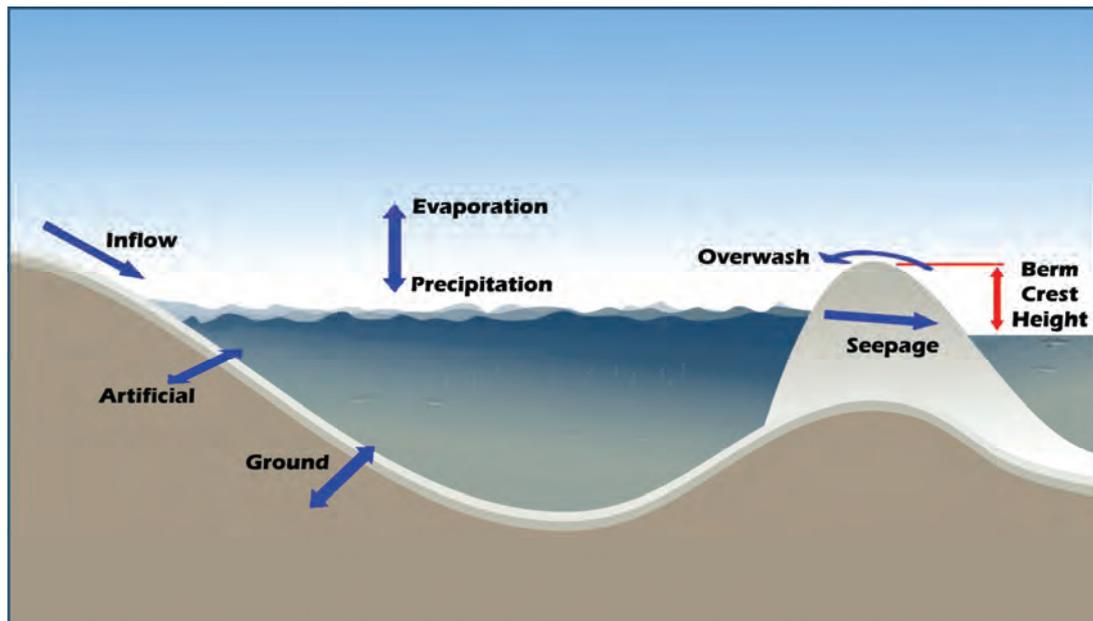


Figure 7-1: Water Balance in a closed estuary

### 7.1.1 SIMPLIFICATION OF THE WATER BALANCE

Studies have shown that  $V_{inflow}$  is usually the dominant natural factor that causes the mouth to breach (Van Niekerk et al., 2008). In small to medium size estuaries, e.g. Palmiet, direct rainfalls contribution  $V_{precip}$  is negligible when compared to  $V_{inflow}$ . This parameter is therefore generally not included in a water model.

The exception to this rule is estuaries with large surface areas or systems that remain close for long periods, as would be the case for the estuarine lake systems such as St Lucia or Swartvlei.

Unless information is available on direct abstraction or discharges,  $V_{artificial}$  can be removed from the water balance calculation. Data on the quantity of water entering or leaving the estuary via the sub-surface flow ( $V_{ground}$ ) are also generally not available, but if the estuary is relatively small in size, the parameter can be treated as negligible when compared to  $V_{inflow}$  in the water balance calculation. However should the estuary remain closed for long periods (e.g. Groen and Spoeg); be in a ground water rich environment (e.g. Swartvlei); subjected to elevated subsurface flows (inflow from dammed Lake Nhlabane to estuary); or have a significant perimeter area (St Lucia) it is critical that this parameter be accounted for.

A combination of specific circumstances usually leads to overwash of the sand berm at the mouth from the seaward side. These are primarily: a low berm crest height; a high tide; and large waves at sea. If the amount and duration of overwash is sufficient, breaching can occur (CSIR, 2003). For example this mechanism were observed at the Great Brak Estuary during a breaching event in 15 May 2002 when the mouth had been closed for 19 days and was flushed open through overwash at a level of 2.24 m MSL (CSIR, 2003). In the case of the Great Brak Estuary, the water level can increase by decimetres in a day or two due to overwash, for example 20 cm On 15-02-2000 and 35 cm in on 19-07-2000 (CSIR, 2000). Thus said, for the purposes of the development of a water balance model for

a EWR study  $V_{\text{overwash}}$  is ignored to simplify model development. It is best to treat overwash as a specific event to assist with determining the envelope of variability within which an estuary responds.

### The inflow from the river ( $V_{\text{inflow}}$ )

River inflow can be either measured or simulated. Less than 10% of coastal catchments have some flow gauging station near the head of the estuary to assist with direct correlation between estuary state and flow. Often the only data valuable is simulated monthly flows. This is not ideal for the numerous smaller estuaries that dominate the South Africa coastline.

Monthly flow data can hide the high degree of variability that occurs in daily flow data, which is synonymous with small catchments. This, in turn, can be linked to rapid changes in mouth conditions and salinity structure. This lack of inflow data at the correct temporal-scale, hampers the determination of Estuary EWRs at a reasonable level of confidence as monthly time steps hides some of rapid state changes smaller systems can fluctuate through and dampens the overall estimation of sensitivity to flow.

### Evaporation from the Estuary ( $V_{\text{evap}}$ )

Evaporation can be calculated from the average surface area multiplied with the A-Pan Equivalent Potential Evaporation (mm) for the area within which the estuary occurs. For each of the 12 evaporation regions of South Africa, each month's Eapan has been expressed as a percentage of the annual Eapan (Figure 7-2) (Schulze and Maharaj, 2007). If only mean annual A-pan equivalent potential evaporation is known, then monthly estimates can be made by applying the relevant region's percentages to the annual value.

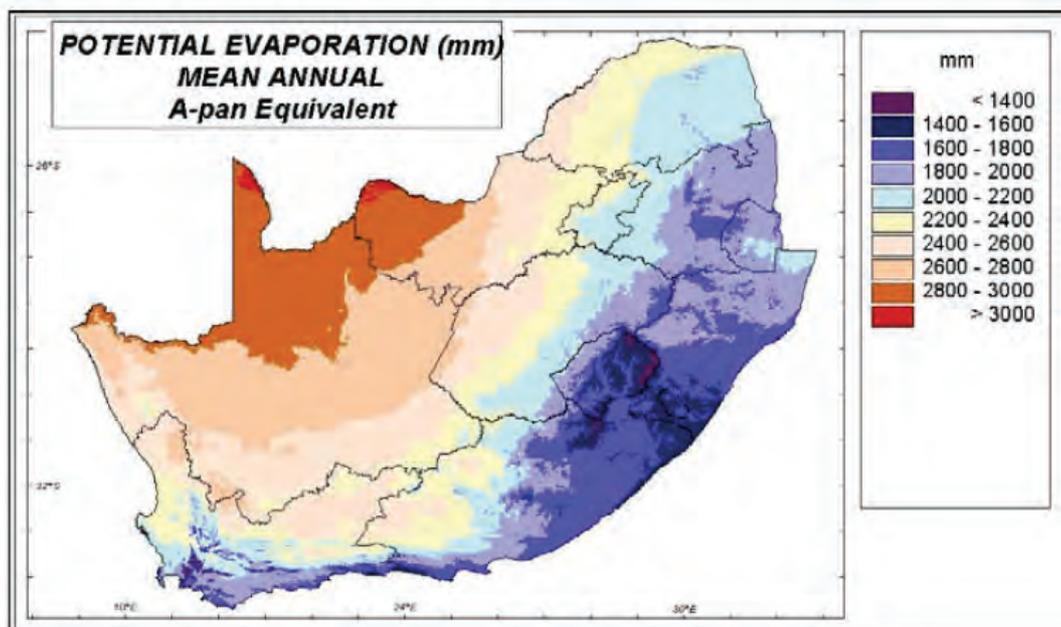


Figure 7-2 Mean annual potential evaporation (mm) A-pan Equivalent (Schulze and Maharaj, 2007)

## 7.2 APPLICATIONS OF THE WATER BALANCE MODEL IN EWR STUDIES

The Water balance models are one of the primary tools of the ERW estuaries studies in South Africa. There are a number of reasons for this:

- Most South Africa estuaries close from time to time and can be treated as a dam, i.e. suitable for water balance/box modelling);
- Water balance models can easily be scaled to the level of certainty required or the data available, i.e. less parameters populated or more coarse data used for Rapid level assessments;
- Basic input parameters can be gathered from aerial photographs, satellite imagery, wave conditions and simulated flow data.
- In particular, most of SA estuaries are small and therefore most parameters do not need to be resolved to a high degree as in most cases processes associated with river inflow are the driving forces of ecosystem state.

The following section will highlight some of the approaches followed in a number of EWR studies over the last decade.

### 7.2.1 ST LUCIA

For the St Lucia RDM study (2003) the classic water balance model was reduced to:

$$V_t = V_{t-1} + V_{\text{inf low}} + V_{\text{precip}} + V_{\text{evap}} + V_{\text{seepage}} + V_{\text{overwash}} + V_{\text{ground}}$$

A simple basin model was developed in which St Lucia was treated as a basin (300 000 000 m<sup>3</sup>) in which inflows from the five river systems (Mkuze, Mzinene, Nyalazi, Hluhluwe, Mpate) feeding directly into the estuary, groundwater, direct rainfall, evaporation and the discharge to and from the sea were combined to estimate the water level of the St Lucia system. The lake levels, in turn were used to evaluate probable mouth conditions and the salinity regime of the system for that month.

For the Reference Conditions it was also assumed that the Mfolozi and St Lucia Estuaries interact at water levels below 0.1 m Mean Lake Level when the St Lucia mouth could close. For the benefit of this evaluation, the monthly runoff from the Mfolozi was used to evaluate the effect of the additional Mfolozi runoff on the St Lucia system mouth conditions. The Mfolozi inflows were only brought into the equation when the St Lucia moth was closed.

The water balance model assumed that the St Lucia Lakes will breach at approximately 3.0 m Mean Lake Level. The past management practises of artificially breaching the estuary at far lower than natural water levels were also evaluated, but the water balance model was not very sensitive to changes in the breaching levels, e.g. lowering the breaching level is to 2.0 M MSL only increased the open mouth conditions by 5%. Therefore for the sake of the Rapid RDM study the mouth breaching level at 3.0 m Mean Lake Level was used. The study found that under reference conditions (St Lucia and Mfolozi mouths joined) the St Lucia Estuary would have been open for 89% of the time, while under the present conditions (St Lucia and Mfolozi separated) the estuary is only open for about 47%

of the time. Salinity was not modelled for this study derived from measured data that correlated with water levels in the estuary.

The above mentioned water balance model was extended and refined by Lawrie and Stretch (2011a). Refinements included subdividing the basin in a number of compartments of various depths based on Hutchison (1974) to allow for more accurate volume estimates, refining the monthly inflow data, quantifying the overflow from Mfolozi under a number of management options. Closure was assumed to have occurred at low lake levels (0.0 mean lake level) by means of a “What if statement”. In addition the refine water balance model also simulated salinities linked to lake levels (Lawrie and Stretch, 2011b). A simplified salt budget was developed that assumed a fully mixed state. Salinity was simulated by means of the following:

$$S_{n+1}V_{n+1} = (S_nV_n - S_nQ_n\Delta t) \quad \text{for } V \geq V_0$$

$$= \left( S_nV_n + \frac{35}{1000}Q_n\Delta t \right) \quad \text{for } V < V_0$$

Where  $S_n$  and  $V_n$  are the lake salinity and volume at the nth time step and  $Q_n$  is the mouth discharge at the nth time step.

The model predicted that St Lucia would have been open for about 80% of the time under Reference Condition and about 70% of the time under Present condition if it were to be linked to St Lucia. A copy of the water balance model will be available from the online repository associated with the forthcoming book on the St Lucia Ecosystem by Perissinotto R, Stretch DD, Taylor, R (eds) (2012).

## 7.2.2 SWARTVLEI

Similarly, the Swartvlei Estuary EWR (Rapid level) was evaluated by means of a water balance with the major input parameters as:

$$V_t = V_{t-1} + V_{inf\ low} + V_{precip} + V_{evap}$$

A simple water balance model was developed in which river inflows into the estuary were accumulated to estimate the volume and water level in the system. The volume, in turn was used to evaluate probable mouth conditions and the salinity regime of the system. The simulated average monthly flows were used as input.

The mouth of the Swartvlei estuary is sensitive to high wave conditions (coupled with a reduction in runoff) as it shows a tendency to close during the winter when high waves tend to occur more frequently. Unfortunately, a long-term record (84 years) did not exist of the wave conditions along the South Coast. The water balance model therefore incorporated mouth closure by artificially closing the estuary mouth in May. This allowed for a comparison between scenarios for the period the systems stays closed due to changes in river inflow to the estuary.

Mouth closure occurred between 0.5 m MSL and 1.0 m MSL. For the purpose of the water balance model mouth closure was taken to occur at a water level of ~0.8 m MSL. The relationship between the height of the berm and periods between breachings, i.e. the longer the system was closed the higher the berm was not addressed as part of the water balance model.

The Swartvlei Estuary is artificially breached at about 2.0 M MSL. In the recent past the estuary was even breached between 1.5 and 1.8 m MSL. The Swartvlei System natural breaching levels were estimated as 3.5 m MSL (Fijen, 1995). As the water balance model is based on monthly time steps Swartvlei's sensitive to the neap-spring-neap tidal cycle (more closures occur on or after a neap tide than a spring tide) was not incorporated.

In general, the higher the water level in an estuary before a breaching event, the more efficient the scouring of sediment in the estuarine channels and mouth area during a breaching, resulting in longer periods of open mouth conditions after the breaching. This relationship is especially important in the case of the estuarine lakes as a small increase in breaching level results in significantly more outflow at breaching, i.e. significant increase in scouring potential. Based on the Swartvlei water level recording data (DWA Station K4R002) and mouth observation data (SANparks) a relationship was established between the water level before a breaching and the period the mouth stayed open after a breaching event.

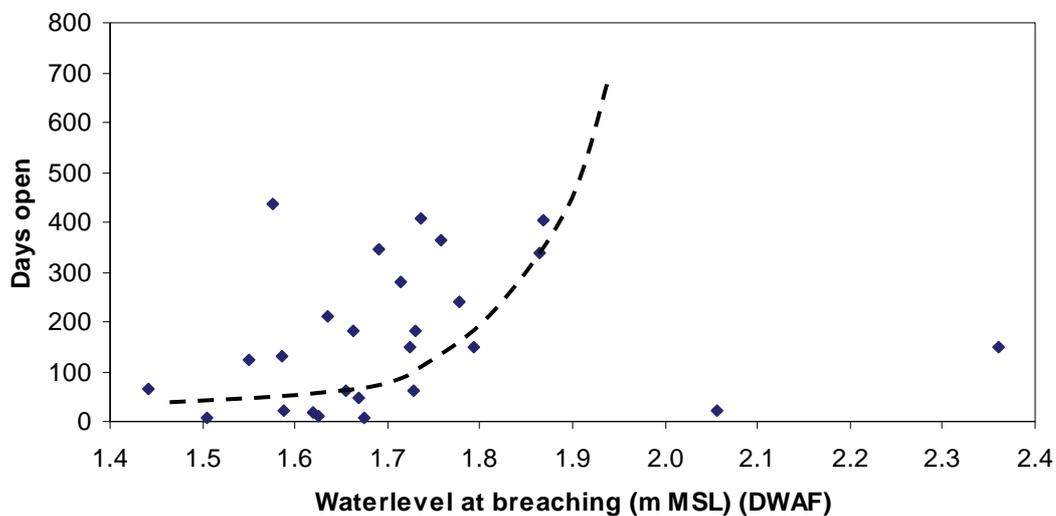


Figure 7-3 Relationship between water level at breaching (DWA STATION K4R002) and days open

According to this relationship the Swartvlei mouth would close on average within about 2 months at a breaching level of ~1.5 m MSL and remain open for up to 3 years at a breaching level of ~3.5 m MSL. This sensitivity to breaching water levels was incorporated in water balance model in the form of an assumption that the Swartvlei estuary would not closed within 12 months of a natural breaching due to the effective scouring of sediment from the mouth area. This is a somewhat conservative estimate as the system may well have been able to maintain open mouth condition in the excess of two years under low flow conditions. At present, baseflows play an important role in maintaining open mouth conditions in the absence of effective scouring.

Based on a surface area of about 14 200 000 m<sup>2</sup> the Swartvlei requires about 14.2 x10<sup>6</sup> m<sup>3</sup> of water to breach at the present breaching level of ~2 m MSL. At the natural breaching level of ~ 3.5 m MSL it would have required about 38.34 x10<sup>6</sup> m<sup>3</sup> to breach (Fijen, 1995).

Seepage was estimated to be ~ 0.4 m<sup>3</sup>.s<sup>-1</sup> to 0.8 m<sup>3</sup>.s<sup>-1</sup>, depending on the water level in the estuary behind the berm. It was assumed that losses due to seepage were cancelled out by groundwater

inflow from the surrounding areas (Fijen, 1995). The overwash was not included in the water balance model as overwash events remain a constant, i.e. sea conditions do not change.

The water balance model was validated against SANParks mouth observations for the period 1993 to 2002. Results indicated that the Swartvlei estuary would benefit significantly from higher breaching levels and are very dependent on river inflow to maintain its connectivity with the sea.

### 7.2.3 MDLOTI, MLANGA AND GREAT BRAK

In small estuaries (< 100 ha) river inflow is the dominating factor. This relationship can be determined through correlating mouth conditions with inflow or calculated. For such systems the classic water balance model is reduced to a simple exceedance relationship, i.e. if inflow exceeds the volume of the estuary it will be open.

In smaller estuaries, the total volume of the system is estimated as the area of the system multiplied by the height the water needed to fill it to breaching level, i.e. the difference between the breaching level and the closing water level.

$$V = Area.(H_{breach} - H_{closed})$$

In temporarily open/closed estuaries area can vary significantly between observations, depending on the degree of backflooding/water levels. It is therefore recommended that a range of areas be used for this calculation to test the EFR results to this parameter, varying from just open water area during open mouth conditions to the 5 m MSL contour. On a high energy coastline closure will occur within less than month of flow decreasing below the estimated flows need to maintain open mouth conditions, while at a more protected estuary mouth closure may only occur after a few months. The rate of closure can be incorporated as delaying factor or counter.

### 7.2.4 LITTLE AMANZINTOTI AND MBOKEDWENI

Some small estuaries operate at very short time scales and phases through open and closed mouth states in less than a day. Observational data show a very high degree of scatter in these cases. Frequently such systems are only open for a few hours at a time. For such systems estimated volume required to breach the system needs to be adjusted to the rate at which the berm can build.

Perissonotto *et al.* (2004) shows that in KwaZulu-Natal a sand berm near the mouth of an estuary can up in 7 days to near its maximum. While data of the Great Brak shows that it can take up to four weeks to reach similar maximum levels. It is expected that in more protected system the rate of berm accretion can even be slower, varying between six to 12 weeks to maximum levels.

Therefore the volume used in the water balance model needs to be adjusted to the timescales of the rate of closure and how often the simulated monthly flow is in that flow range.

### 7.3 PROTOTYPE MODEL THAT LINKS RIVER INFLOW TO BERM HEIGHT

The primary objectives of this section were to develop a numerical model to quantify and predict breaching of estuaries, and to determine which environmental variables needed to be monitored to improve the estimates. The overall aim is to enhance the understanding and quantification of factors affecting estuary mouth dynamics.

The Groot Brak Estuary was chosen for the case study as a long term record on the river inflow, estuarine and coastal parameters and mouth state is available. Another important criterion for selecting the estuary was that the mouth condition changed relatively frequently providing sufficient data for the development of the numerical model. The time-period was chosen to concur with breaching events for which sufficient input data was available for model setup and calibration.



Figure 7-4 The Groot Brak Estuary

#### 7.3.1 MODEL CONCEPTUALISATION AND FORMULATION

The Groot Brak Estuary is a small to medium size estuary and lies in a low rain fall zone (< 400 mm per year). The direct rainfall contribution is therefore negligible when compared to  $V_{\text{inflow}}$  and therefore not included in the model. There are also no artificial in- or outflows to Great Brak. Data on the quantity of water entering or leaving the estuary via the sub-surface flow ( $V_{\text{ground}}$ ) were not available, but as the estuary is relatively small in size the parameter was also treated as negligible when compared to  $V_{\text{inflow}}$  in the water balance calculation. While overwash can increase the Great Brak water level by decimetres in a day or two during storm events, for the purposes of the development of a numerical model  $V_{\text{overwash}}$  was discounted to simplify model development with the intention of adding it in the next development cycle. River inflow is measured by the Department of Water Affairs. The original data was expressed in cubic metres per second ( $\text{m}^3 \cdot \text{s}^{-1}$ ) from which total daily inflows were calculated.

Evaporation was taken to be a constant throughout the period, with a daily evaporation rate of about 2210 m<sup>3</sup>. This was derived from the annual evaporation estimated at 1300 mm over the average surface area of the Groot Brak Estuary (620 000 m<sup>2</sup>) (Jezewski and Roberts, 1986).  $V_{\text{seepage}}$  was estimated at 0.121 m<sup>3</sup>.s<sup>-1</sup> (DWAF, 1990).

A model was formulated so that it would calculate the water volume in the estuary on a daily basis using a water balance model and then convert the total volume to a water level elevation by means of an area-water level relationship.

$$V(t) = 148501 \cdot WL(t)^2 + 215972 \cdot WL(t) - 16634$$

The resultant water level elevation was then compared to the estimated berm crest height for both the Swart and Nielsen & Hanslow methods. Once the simulation detected that the water level was greater than or equal to the berm crest height, a breach was simulated and the breaching level and number of days taken before the breach was reported.

In order for a simulation to progress past the first time step, initial input values were required in order to calculate successive values for the volume of water in the Estuary and the Berm Height. The initial input value for water level was taken as the mean water level for the values that were recorded on the starting day of the simulation. The required initial value for berm height was selected to be large enough so that the model would not report a breach to occur on the first time step, yet small enough so that the value would be updated at some point during the run (when wave conditions dictated). One of the tests was to see that the berm height had been increased at least once before a breach was calculated.



Figure 7-5: The Groot Brak Estuary Mouth just after (assisted) breaching

### 7.3.2 RESULTS

The output of a typical run for the model is shown for a berm height calculated via the Swart as well as the Nielsen & Hanslow methods (Figure 7-6 and Figure 7-7).

#### Model run with Seepage and Evaporation terms included

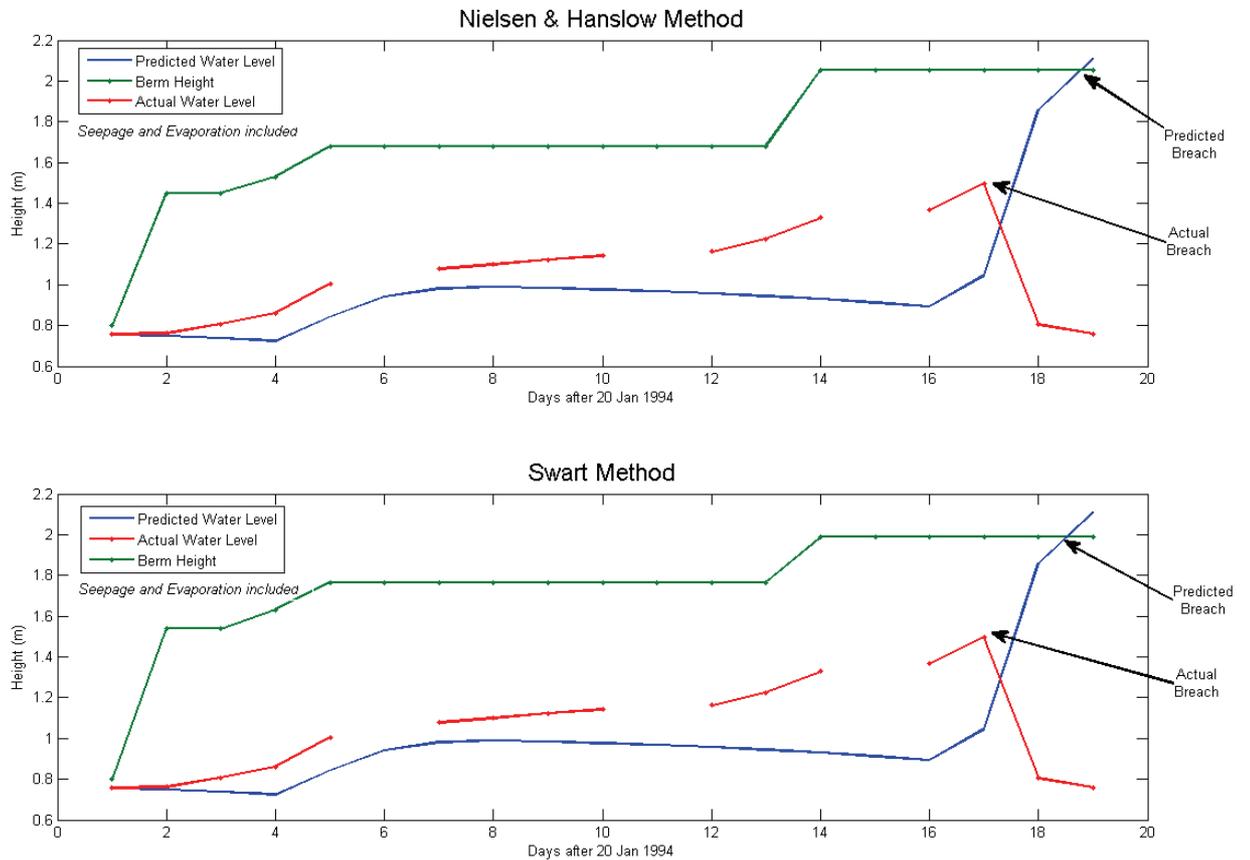


Figure 7-6: Combined plot of predicted and actual water levels in the Estuary and Berm Height over time Seepage and Evaporation effects are included.

An additional comparison was conducted between the actual water level data in the Groot Brak Estuary at the time of a breach, and the calculated berm height using each of the above methods. During this comparison, the value calculated via the Nielsen & Hanslow method was further adjusted by a constant of 1.22 m. Figure 7-8 and Table 5.2 shows the results of this comparison. It is important to note that the figure below includes data derived from artificial breaches. Though not entirely accurate, the berm height at the time of an artificial breach has been observed to be reasonably close to that of the water level.

## Model run without Seepage and Evaporation

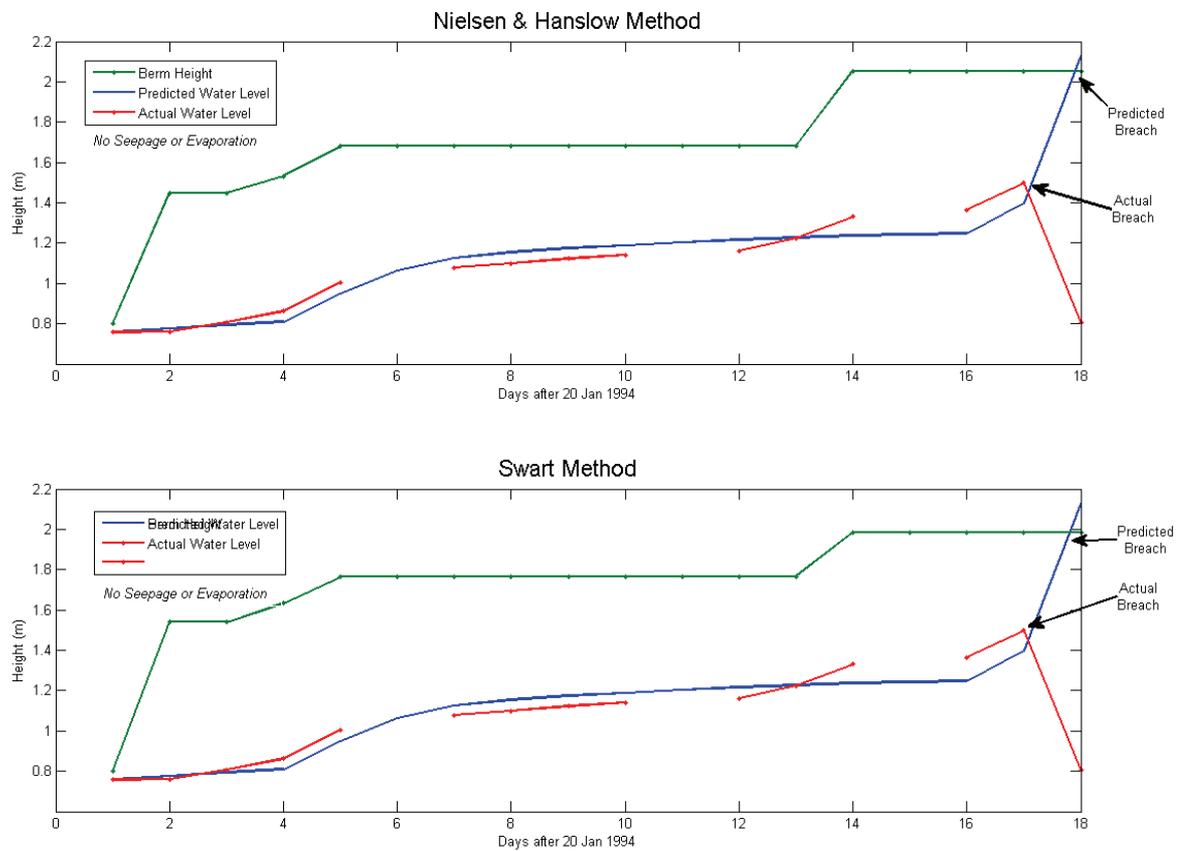


Figure 7-7: Combined plot of actual and predicted water levels in the estuary and Berm Height over time. Seepage and Evaporation are not included.

The table below summarises the results of the model run.

Table 7.1 Summary of model results indicating days to breaching and predicted berm height.

Method	Days to Breach	Predicted Berm Height at breach (m)
Actual Data	16	1.50
N&H Method (incl. seepage and evap.)	18	2.05
Swart Method (incl. seepage and evap)	18	1.99
N&H Method (excl. seepage and evap)	17	2.05
Swart Method (excl seepage and evap.)	17	1.99

## Predicted berm crest levels vs. breach wl data

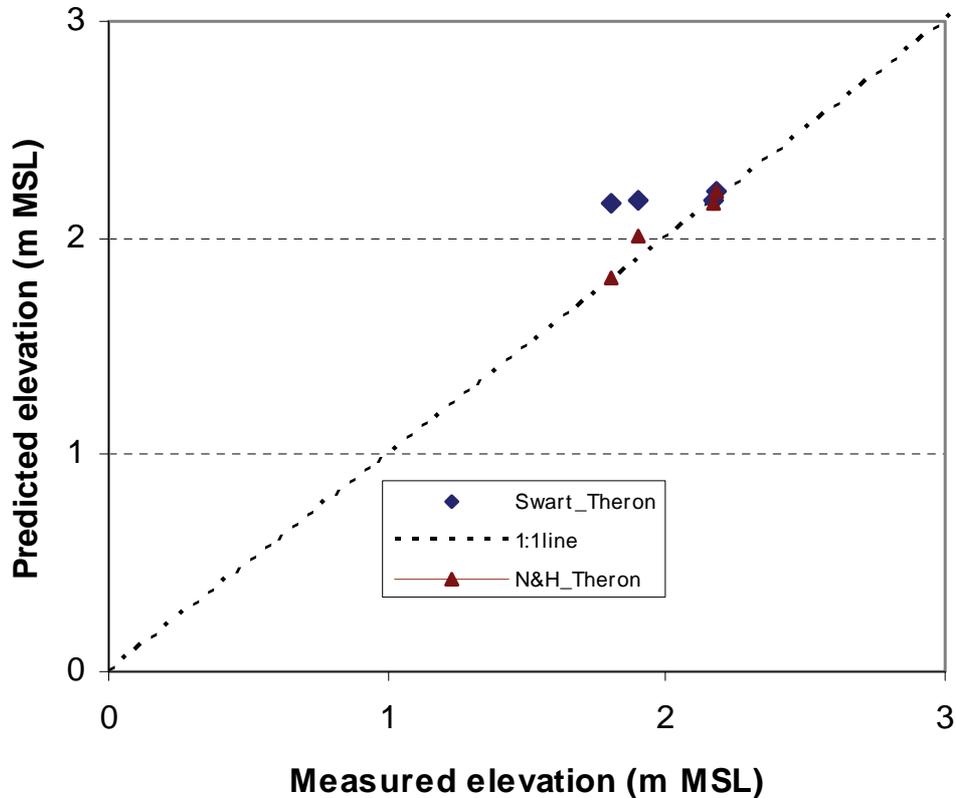


Figure 7-8: Measured water level at the time of breach of the Groot Brak Estuary against the calculated value for berm height using the Swart (blue diamonds) as well as the Nielsen & Hanslow (red triangles) methods.

### 7.3.3 CONCLUSIONS AND RECOMMENDATIONS

The simulated result for both methods compare well with the measured data. Both the timing of the breaches and the berm crest heights at the time of the breaching compared well. The estimate calculated with the Nielsen & Hanslow method, performed better than the Swart method as it resulted in a berm crest height which was closer to the actual water level at the time of the breach.

The study also identified the following factors which need to be monitored or investigated in order to improve on the accuracy of the model:

The height of the berm needs to be accurately measured at different estuaries to verify the general applicability of the two berm crest elevation prediction models. When calculating the Berm Height with the Nielsen & Hanslow method, it was assumed that the Mean Water Level would remain constant during the period through which the model was run. By including the effects of the tides on the Mean Water Level, a more accurate estimate of the Berm Height could be ascertained. The results however show that the predicted berm crest levels are close to the water level at the time of the breach. This is very promising as, in the absence of actual berm crest height data, an estimate can be made which says that at the time of a breach, the berm crest height should be equal or very nearly

equal to the water level within the estuary. This assumption in turn allows us to derive the berm crest height at the time of a breach. By noting that the actual breaching water level and the calculated berm crest height are within a reasonable range, the methods detailed in the model can be used to estimate the berm crest height for any desired period of time.

The initial objective of this exercise was to develop a tool that would assist estimating the EWR for estuaries in South Africa. The model will be able to do this, however it should be pointed out that some of the data requirements are costly. If these data requirements are not adequately addressed the model may yield results that are of low accuracy. Data requirements include: a water level to water volume relationship for a particular estuary; a daily estimate of river runoff for to enable the model to the water levels in the estuary and an evaluation of the wave climate over the modelling time period.

At present most South African ecological water requirements studies in South Africa use a correlation approach where river inflow and mouth state data are available. Results show that a generally a good relationship can be found between flow and mouth state if data is available. A criticism of this approach is that extreme values (e.g. rapid mouth closure, very high water levels) caused by high wave action or other coastal parameters are often discounted as anomalies as they are hard to predict under average conditions.

The model developed here can be used to quantify some of the coastal parameters affecting the state of mouth of the estuary and help to understand the variability in breaching patterns. The model can also be used in data poor estuaries (e.g. Transkei coast) where river inflow, water level and mouth state data is lacking. This tool offers greater insight into the system dynamics and enable quantitative predictions, which otherwise would usually be lacking or based on expert opinion.

## 8. SALINITY PENETRATION

**Problem:** *It is very difficult to predict the change in salinity distribution in permanently open estuaries in response to flow modification as there is very little good historical data (e.g. long-term inflow and salinity data) available in SA.*

**Response:** *Initially develop, and later adopt internationally recognised 1-dimensional numerical models (e.g. Mike 11) to predict the salinity distribution in a permanently open estuary under various flow scenarios (including natural conditions). This approach were further refined to include 3-dimensional modelling (e.g. Delft 3D) in the case of systems where a high degree of stratification were observed (e.g. Kromme, Knysna) to more accurately predict retention/flushing times and salinity distribution (Van Ballegooyen et al., 2004).*

The saline intrusion in an estuary is regulated by tidal amplitude, river inflow and bathymetry (size and shape) of an estuary (Prandle, 2009). The salinity distribution and structure may be altered by anthropogenic actions such as dredging (deepening of estuary), barrier constructions (preventing further salinity penetration) or flow modification (reduction in flow leads to increase penetration and an increase in flow to reduce penetration).

Changes in the salinity intrusion may have implications for water geochemistry, sedimentation (e.g. flocculation zone may change) or the dispersal of pollutants. Whereas tidal propagation can be relatively easily calculated from simple analytical formulas and therefore accurately modelled, it is more difficult to derive an accurate prediction of salinity intrusion from neap to spring or flood to drought.

Saline intrusion involves a range of interactions, under a range of temporal and spatial scales, including (Prandle, 2009):

1. The tidal cycle, with vertical mixing occurring on the peak flood and ebb tide due to bottom friction.
2. Neap-spring cycle, with mixing more pronounced on the spring tide.
3. Hydrological cycle, with stratification more pronounced under elevated inflows;
4. Storm events, e.g. storm surges increasing penetration;
5. Variations in water density due to other factors, in particular temperature and suspended sediment load (considered less important in estuaries).

The salinity structure can be expressed in a number of manners depending on the available data and the level of study. Hansen and Rattray (1966) described salinity structure by means of a stratification-circulation classification based on the densimetric Froude number. Fischer (1972) described stratification by the estuarine Richardson number, which evaluates the ratio of the gain of potential energy due to the runoff discharge to the mixing power of the tide. In contrast, Simpson et al., 1990 focused on the degree of stratification in an estuary by the amount of energy input needed to break down the stratification.

## 8.1 MEASURE DATA/CORRELATION APPROACH

Ideally, enough observational river inflow and salinity records would exist to allow for a statistically validated correlation model to be developed, e.g. similar to the Texas Flow approach. Unfortunately in South Africa data poor environment this is very seldom achievable as both continuous flow records and long term salinity records are a scarcity. There are very few examples of where this was possible, the exceptions here is the Comprehensive Berg RDM that followed a two year long monitoring programme.

Seasonal salinity distributions in the Great Berg Estuary based on quarterly measurements collected during the period 2002 to 2005 showed a distinct longitudinal seasonal distribution patterns, largely driven by the extent of freshwater inflow, i.e. the extent of saline intrusion decreases with an increase in freshwater inflow. For example, during the dry season (February), saline waters penetrated well into upper reaches, while in the wet season (August), strong freshwater influence limits saline intrusion to the lower sections of the system. Field measurements showed that the Great Berg Estuary was well-mixed. Stratification seldom occurred, and did not seem to last very long, probably because of strong mixing from tidal exchange and fresh water inflow. It was therefore considered appropriate to integrate salinity and other water quality data over water depth at each station, using a mean value for each station. The data showed a strong correlation with flow.

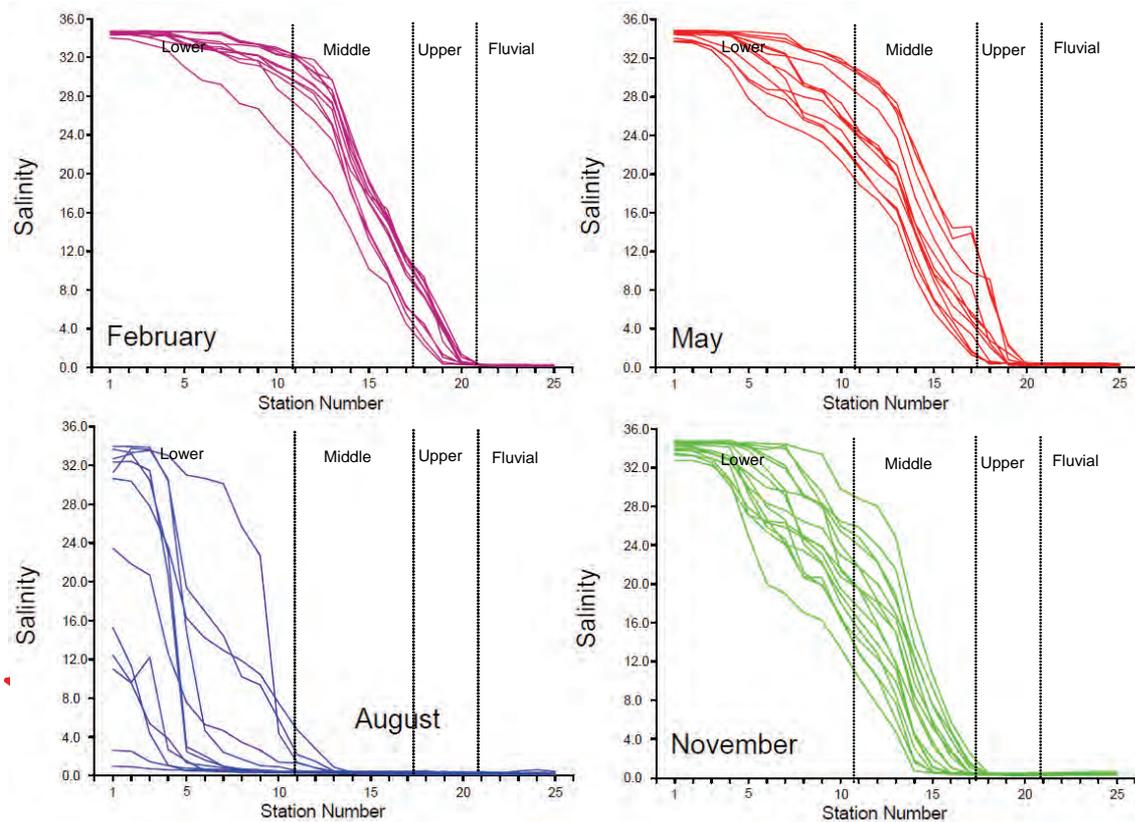


Figure 8-1: Vertically-integrated salinity distribution in the Great Berg Estuary from 2003 to 2005 representative of a particular seasonal distribution (DAAF, 2010). Also indicated on the graphs are the different zones and

## 8.2 SALT BALANCE MODEL

The refined water balance model developed by (Lawrie and Stretch, 2011a and 2011b) includes a simplified salt budget model that assumes a fully mixed state. Salinity was simulated by means of the following:

$$\begin{aligned} S_{n+1}V_{n+1} &= (S_nV_n - S_nQ_n\Delta t) \quad \text{for } V \geq V_0 \\ &= \left( S_nV_n + \frac{35}{1000}Q_n\Delta t \right) \quad \text{for } V < V_0 \end{aligned}$$

Where  $S_n$  and  $V_n$  are the lake salinity and volume at the  $n$ th time step and  $Q_n$  is the mouth discharge at the  $n$ th time step.

Lawrie and Stretch (2011a and 2011b) used long-term simulations of the water and salt balance to estimate the occurrence and persistence of water levels and salinities for different management scenarios. The risks of desiccation and hyper-salinity were assessed for each case. The results show that the configuration of the Mfolozi/St Lucia inlets plays a key role in the physicochemical environment of the system. Without the Mfolozi link desiccation (of about 50% of the lake area) would occur for 32% of the time for an average duration of 15 months. Artificially maintaining an open mouth would decrease the chance of desiccation but salinities would exceed 65 about 17% of the time. Restoring the Mfolozi link would reduce the occurrence of both desiccation and hypersaline conditions and a mostly open mouth state would occur naturally.

## 8.3 ONE DIMENSIONAL (1D) NUMERICAL MODELLING

In permanently open estuaries it is very difficult to predict the extend of salinity penetration under different flow conditions. The best tool to solve this is numerical modelling of an estuary's response to flow changes.

An example of such a 1D numerical model is the Mike 11 software package that comprises a hydrodynamic module and a transport dispersion module. The hydrodynamic module is based on the solution of the Saint Venant equations of continuity and momentum for one dimensional flow by implicit finite difference techniques.

The continuity equation:

$$\delta Q/\delta x + \delta A/\delta t = q$$

The momentum equation:

$$\delta((\alpha Q^2)/A)/\delta x + \delta Q/\delta t + gA(\delta h/\delta x) + (gQ|Q|)/C^2AR = 0$$

The hydrodynamic model is driven by the tidal variation of water levels at the downstream open boundary at the mouth and by the river flow at the upstream open boundary condition. The calibration of the hydrodynamic model is done by adjusting the bottom roughness until a satisfactory agreement is reached between simulated and measured water level variations.

The transport dispersion module is used to simulate the effects of the intrusion of seawater on salinities in an estuary, based on tidal flows at the mouth and the inflow of freshwater upstream. The transport dispersion formula used in the Mike 11 modelling system is:

$$\delta(AC)/\delta t + \delta(QC)/\delta x - \delta(AD(\delta C/\delta x))/\delta x = -AKC + C_2q$$

The transport dispersion module is operated separately, using the same topographical information as the hydrodynamic model. The open boundary conditions on both sides are time series of concentrations associated with the hydrodynamic boundaries, i.e. the concentrations of sea salinity at the mouth and normally zero salinities of the river flow upstream. The transport dispersion model is calibrated by adjusting the dispersion coefficients until a satisfactory agreement is reached between the computed and measured salinity concentrations.

This modelling approach has been successfully used in a number of Intermediate level EWR studies, e.g. Olifants and Breede. See Appendix B for more detail on the Breed case study.

#### 8.4 THREE DIMENSIONAL (3D) NUMERICAL MODELLING

DELFT3D-FLOW 3D hydrodynamic model have been applied to a number of estuaries in South Africa (Kromme, Berg, Knysna and Palmiet). It was generally selected for its ability to resolve stratification. It has also been used to resolve flooding issues (e.g. Berg)

The DELFT3D-FLOW hydrodynamic model includes formulations and equations that take into account:

- Tidal forcing;
- Wind shear stress on the water surface;
- Wave-driven flows;
- Bed shear stress at the seabed (including wave effects);
- Drying and flooding on tidal flats;
- The effect of the earth's rotation (Coriolis force);
- Free surface gradients (barotropic effects);
- Horizontal gradients in pressure due to changes in water density (baroclinic effects);
- Water with variable density due to temperature or salinity differences (equation of state);
- Turbulence-induced mass and momentum fluxes (k-ε turbulence closure model);
- Insolation and air-sea interactions at the sea surface;
- Transport of conservative constituents (advection-diffusion equation).

The system of equations in DELFT3D-FLOW comprise the horizontal momentum equations, the continuity equation, the equation of state, the advection-diffusion equation for heat, salt and other conservative tracers, as well as formulations which take into account the role of insolation and air-sea fluxes in determining the stratification of the water column. The equations and their numerical implementation are described in detail in WL|Delft Hydraulics (2005). Simplified versions of these equations follow.

Conservation of momentum in x-direction:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial \eta}{\partial x} - f \cdot v + \frac{g \cdot u / |U|}{C^2(d + \eta)} - \frac{F_x}{\rho(d + \eta)} - \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) = 0$$

Conservation of momentum in y-direction:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial \eta}{\partial y} + f \cdot u + \frac{g \cdot v / |U|}{C^2(d + \eta)} - \frac{F_y}{\rho(d + \eta)} - \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) = 0$$

Conservation of mass, continuity equation:

$$\frac{\partial \eta}{\partial t} + \frac{\partial [(d + \eta)u]}{\partial x} + \frac{\partial [(d + \eta)v]}{\partial y} = 0$$

where:

$\eta$	=	water level elevation (m)
$d$	=	water depth (m)
$u, v$	=	velocity in the x-, y-directions, respectively ( $m \cdot s^{-1}$ )
$U$	=	magnitude of total current velocity ( $m \cdot s^{-1}$ )
$F_{x,y}$	=	x- and y-components of external forces (Pa)
$f$	=	Coriolis parameter $2\Omega \sin\theta$ , where $\Omega$ is the earth's angular velocity and $\theta$ is the geographic latitude ( $rad \cdot s^{-1}$ )
$g$	=	acceleration due to gravity ( $m \cdot s^{-2}$ )
$\rho$	=	water density ( $kg \cdot m^{-3}$ )
$\nu$	=	eddy viscosity ( $m^2 \cdot s^{-1}$ )
$C$	=	Chézy coefficient ( $m^{1/2} \cdot s^{-1}$ )

The model incorporates a sophisticated  $k-\epsilon$  turbulence closure scheme (WL|Delft Hydraulics, 2005).

The constituents of the water in the estuary are simulated using an advection-diffusion equation as indicated below.

Advection-diffusion equation:

$$\frac{\partial c}{\partial t} - \frac{\partial}{\partial x} \left( D_x \frac{\partial c}{\partial x} - u \cdot c \right) - \frac{\partial}{\partial y} \left( D_y \frac{\partial c}{\partial y} - v \cdot c \right) = Source - Sink$$

where:

$c$	=	constituent, e.g. salinity, temperature
$u, v$	=	current velocity in the x-, y-directions, respectively ( $m \cdot s^{-1}$ )
$D_{x,y}$	=	dispersion coefficients in the x-, y-directions ( $m^2 \cdot s^{-1}$ )
Source	=	source term, e.g. heat influx when the constituent modeled is temperature
Sink	=	sink term, e.g. atmospheric heat loss when the constituent modeled is temperature

The horizontal turbulent dispersive transport of momentum and other constituents, such as temperature, are computed using prescribed eddy viscosity coefficients and eddy diffusivity coefficients, respectively. The vertical eddy viscosity and eddy diffusivity coefficients are computed by a  $k-\varepsilon$  turbulence closure model. The shear stress ( $\tau_{seabed}$ ) at the seabed induced by turbulent flow is assumed to be given by a quadratic friction law:

$$\tau_{seabed} = \rho \cdot \frac{g}{C_{3D}^2} |u_b|^2$$

where  $u_b$  is the near-bottom current speed and  $C_{3D}$  is a function of  $C_{2D}$  given by the White Colebrook formulation (WL|Delft Hydraulics, 2005):

$$C_{2D} = 18 \log_{10} \left( \frac{12H}{k_s} \right)$$

where  $H$  is the total water depth (m) and  $k_s$  is the Nikuradse roughness length (m).

The relationship between the three-dimensional Chézy co-efficient,  $C_{3D}$ , and the two-dimensional Chézy co-efficient,  $C_{2D}$ , is as follows:

$$C_{3D} = C_{2D} + \frac{\sqrt{g}}{\kappa} \ln \left( \frac{\Delta z_b}{2H} \right)$$

Enhanced bed stresses due to wave effects are incorporated in the model using the friction formulation of Fredsøe (1984).

The magnitude of the wind shear stress on the water surface is modelled by the following quadratic expression

$$\tau_{wind} = \rho_a \cdot C_D (U_{10}) \cdot U_{10}^2$$

where:

$\rho_a$	=	<i>density of air (kg.m-3)</i>
$C_D$	=	<i>wind drag coefficient which is typically a function of wind speed</i>
$U_{10}$	=	<i>wind speed 10 m above the water surface (m.s-1)</i>

In the horizontal direction an irregularly-spaced, orthogonal, curvilinear grid is used. In the vertical direction use is made of a sigma-coordinate grid that results in a constant number of layers over the horizontal computational area. The thickness of the layer is thus proportional to the water depth at each horizontal position. An “anti-creep” procedure is available that is designed to limit numerical diffusion associated with the use of sigma-coordinates.

The time integration method used to solve the equations in DELFT3D-FLOW is the Alternating Direct Implicit type where the water levels and velocities are solved implicitly along grid lines. The accuracy of wave propagation in the grid is related to the Courant number. An appropriate time step is typically determined by comparison of the relevant model results for successively decreasing time

steps (*i.e.* the time step is halved in successive simulations until further changes in the model outputs are negligible).

Of greatest importance is the accurate resolution of the major bathymetric features of an estuary, that includes the generally shallow upstream bathymetry, the complicated channels of the middle and lower estuary, the extensive tidal flats in the system and the bathymetry (sandbars) in the mouth of the estuary between the heads.

Typically the first step in the calibration of the DELFT3D-FLOW model is undertaken using water level data at a number of sites along the length of the estuary. In the calibration procedure, typically the discrepancies between the observed and modelled results are minimised by “tuning” model parameters such as boundary conditions (tidal amplitudes), depths, storage volumes and bed roughness. Further calibration of the DELFT3D-FLOW model is then undertaken using the most conservative tracer, salinity, as on the time scales being simulated it is a reflection of the model transport (advection and diffusion) only.

Using the modeling results estimates can be made of the persistence of low salinity conditions after a freshette of flood event. This persistence is estimated as the duration that salinities lower than the “mean” salinity distributions due to a steady base flow of 1 m<sup>3</sup>/s. A recovery threshold of 85% to 95% of the measured salinities prior to the event is used to make the estimates of persistence of low salinity conditions.

Table 8.1 Example of the estimated duration of the persistence of low salinity conditions in the Knysna Estuary due to various inflow conditions.

<i>Flows (m<sup>3</sup>/s)</i>	<i>Location</i>		
	<i>Railway bridge</i>	<i>N2 Bridge</i>	<i>Red Bridge</i>
300	10d	26d	26d
200	9d	26d	25d
100	9d	22d	23d
50	7d	20d	13d
30	5d	15d	12d
25	5d	13d	12d
20	4d	12d	11d
15	4d	9d	11d
10	3d	8d	10d
5	2d	5d	10d

The residence time or flushing period of the various flow regimes of the estuary can also be estimated using a conservative tracer. At the start of the simulation the whole estuary is filled with a conservative tracer with a nominal concentration of 100. This could be considered to represent a percentage of tracer remaining at the measurement location.

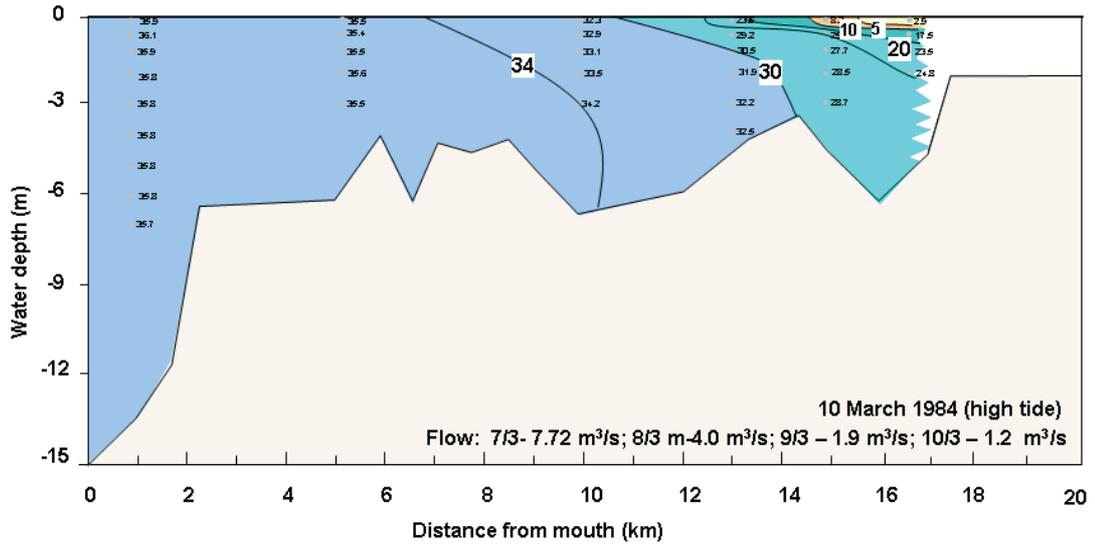


Figure 8-2 Observed longitudinal salinity distributions in Knysna Estuary at high tide on 10 March 1984.

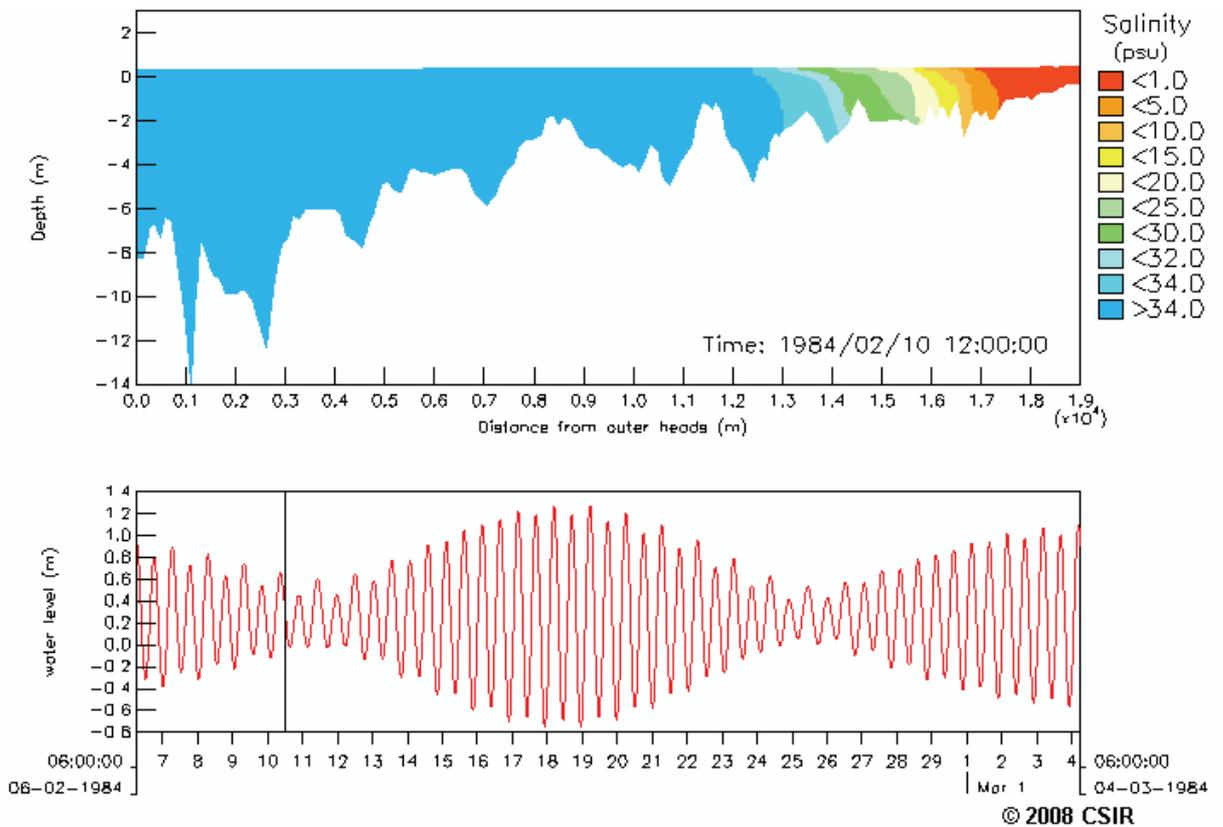


Figure 8-3 Simulated longitudinal salinity distributions in Knysna Estuary at high tide on 10 March 1984.

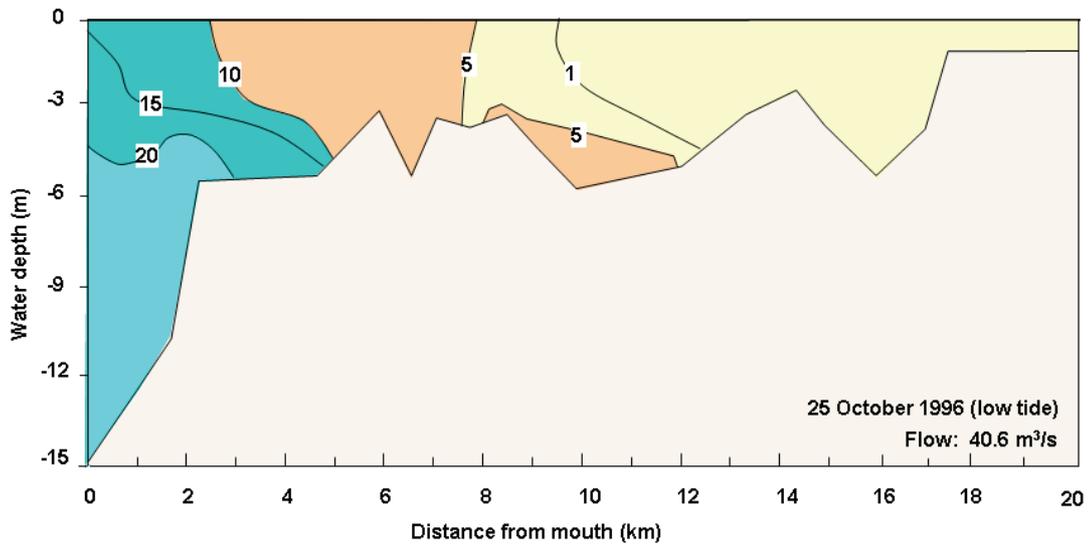


Figure 8-4 Observed longitudinal salinity distributions in Knysna Estuary at low tide on 26 October 1996

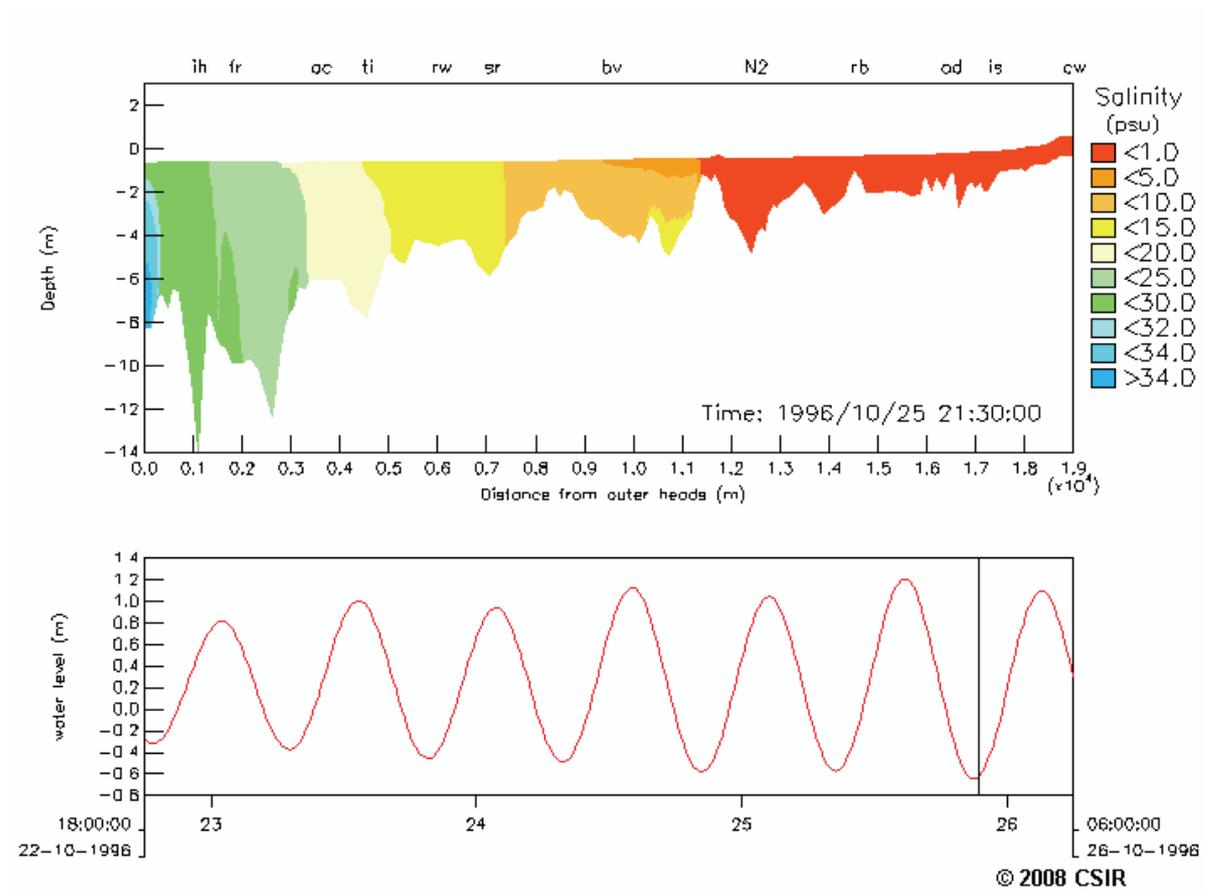


Figure 8-5 Simulated longitudinal salinity distributions in Knysna Estuary at low tide on 26 October 1996.

## 8.5 SELECTING THE CORRECT MODELLING APPROACH

In estuaries physical and biogeochemical processes drive the responses ultimately observed in the biotic components, thus there is a need to characterize abiotic responses as best possible. Predictive tools that can be applied in assessing the hydrodynamics (or water circulation patterns) are numerous. These range from 3D numerical models, 2D numerical models, 1D numerical models, water balance models, statistical relationships to conceptual models (Van Ballegooyen et al., 2004; Largier et al., 1992; CSIR, 1993; Slinger et al., 1997).

The most appropriate technique or model needs to be selected based on the purpose of the study and the complexity of the estuarine system being assessed. One of the situations requiring the implementation of a more sophisticated tool is where the estuary being evaluated is a highly stratified or partially stratified estuary.

Modelling is a representation of the real world with simplifications that are necessary for practical purposes. All models are 'driven' by input data and 'parameters' that allow a generic model to represent a specific situation (i.e. a specific river, catchment or water resources system). Models offer opportunities for adding value to limited observations, but they should not be considered as alternatives to real data.

While 3D modelling is more accurate in highly stratified shallow systems, a major limitation is the computational overhead. Unlike 1D model there is a significant computational requirements in resolving the bathymetric cross-section in an estuary, i.e. the greater the degree of complexity in the bathymetry the greater the number of computational cells required to resolve this complexity. Computational overhead also comes from the need to have large number of vertical layers in the model to resolve vertical stratification in the model, e.g. when dealing with stratification you need 32 layers or more to ensure accurate simulations (Van Ballegooyen et al., 2004)

A simple decision tree for application of numerical modelling is provided (Figure 8.6). Numerical modelling is especially important in permanently open estuaries where the incremental effects of changes in river inflow are very difficult to derive from a number of once-off sampling surveys.

In the final analyse sometimes 'soft issues' such as communicating results intuitively to clients and ecologist count as much as 'hard engineering' approaches that will only look at efficiencies and confidence limits require for study results. While 2D or 3D modelling might be very resource hungry, they communicate results more intuitively and inspire more confidence in a non-engineering environment. Therefore sometimes one would lean towards the more detail modelling approach where there is a high deal of user conflict or a great deal of ecological sensitivity at play.

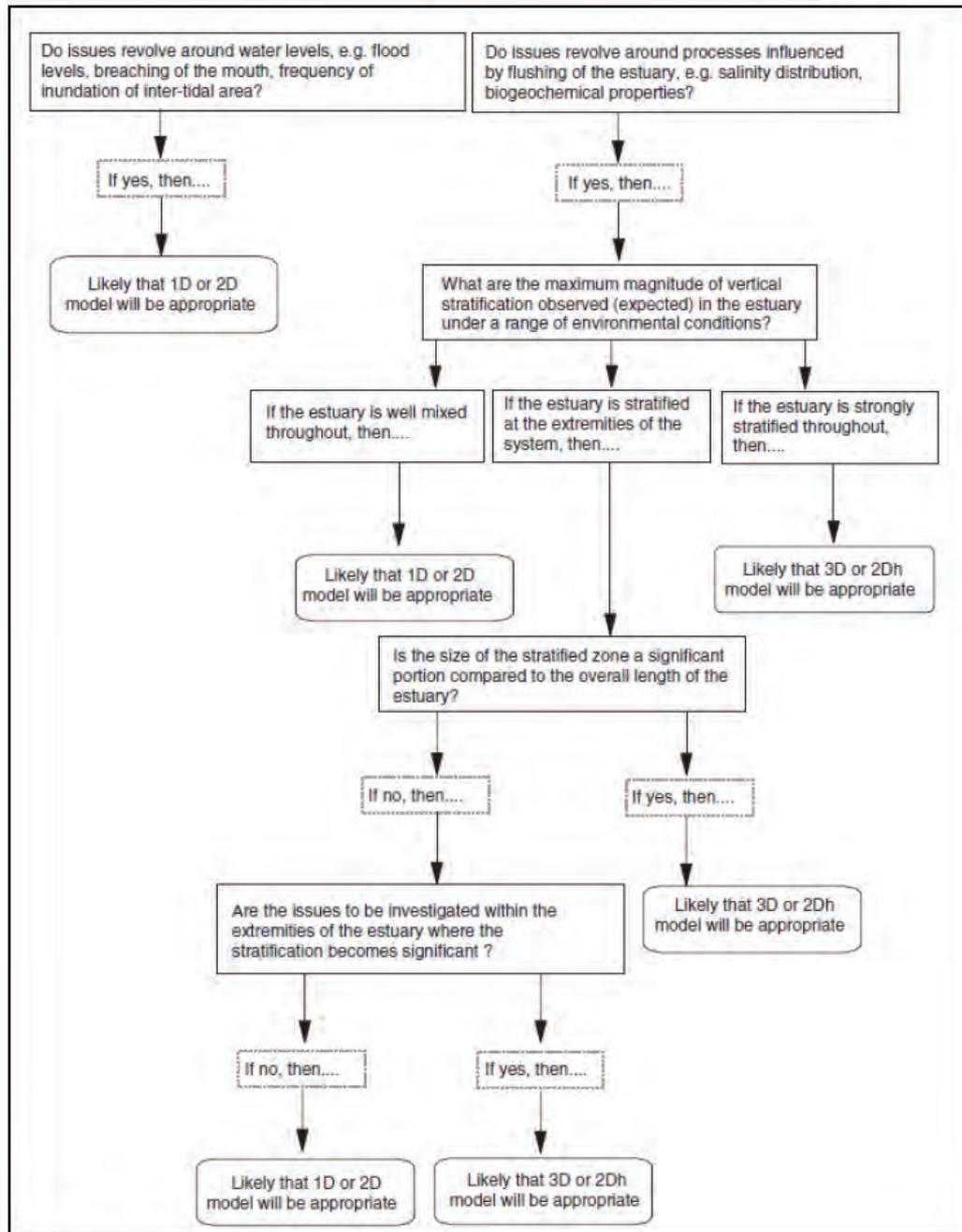


Figure 8-6. A robust decision tree to decide on to type of numerical model to be used for a particular application in estuaries (1D = one dimensional; 2D = two dimensional; 2Dh = two dimensional horizontal; 3D = three dimensional) (Van Ballegooyen et al., 2004)

## 8.6 RETENTION TIME

The residence time of an estuary  $T$  is the volume of water within the estuary ( $V$ ) divided by the flow rate of the river:

$$T = (V / Q_f) (1 - S_1 / S_o - S_f / S_o)$$

Numerical modeling is the most accurate method for calculating the residence time for a range of possible flow conditions. For example, to provide an estimate of the retention times of water masses in the Breede Estuary during low flow conditions, the Mike II model was used to simulate the changes in concentration and distribution of a conservative tracer at a steady flow of  $20 \text{ m}^3 \text{ s}^{-1}$  over a 6-week period (Figure 8-7). The simulation indicated that the maximum retention was in the region 5 to 15 km upstream from the mouth, where already after about 2 weeks less than 50% of the original water mass remains.

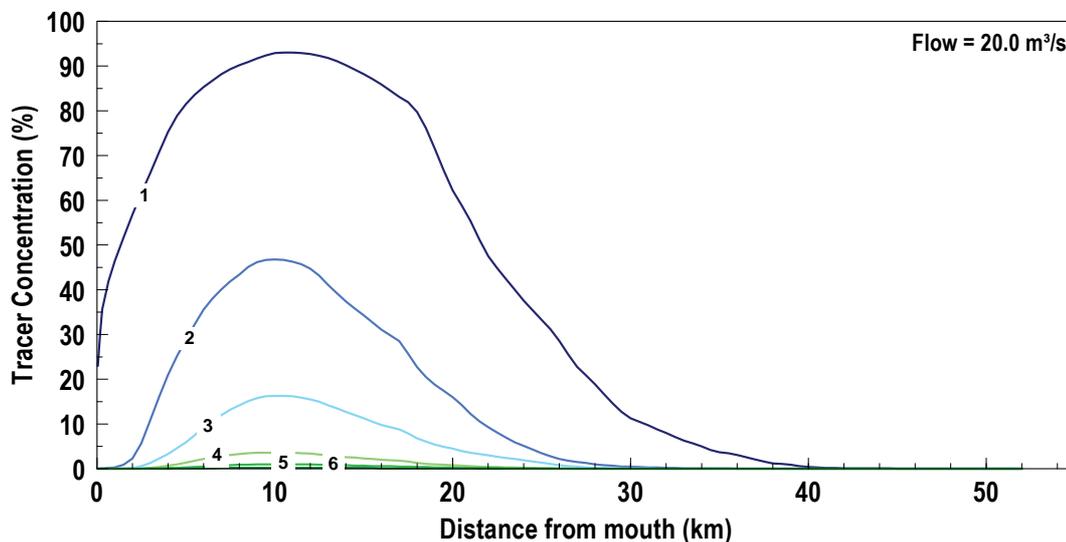


Figure 8-7 Flushing potential of the Breede Estuary at  $20 \text{ m}^3 \text{ s}^{-1}$

In contrast retention times increases dramatically under the low flow condition. The model was also used to simulate the changes in concentration and distribution of a conservative tracer at a steady flow of  $0.5 \text{ m}^3 \text{ s}^{-1}$  over a 24-week period (Figure 8-8). These simulations indicated that the maximum retention was in the region 30 to 50 km upstream from the mouth, where after about 6 weeks only 50% of the original water mass remains.

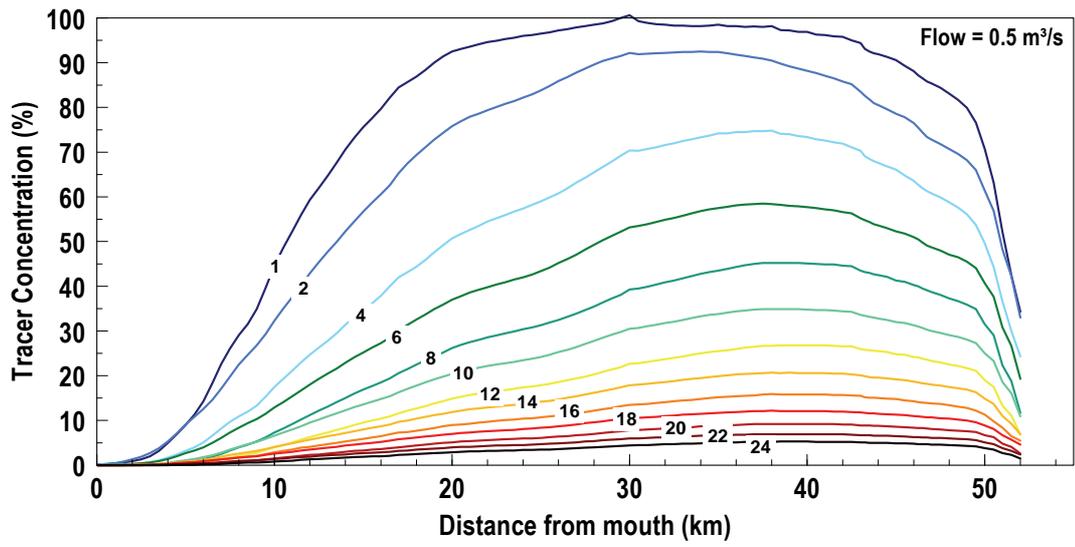


Figure 8-8 Flushing potential of the Breede Estuary at  $0.5 \text{ m}^3 \cdot \text{s}^{-1}$

## 9. AN ECOHYDROLOGICAL METHOD FOR DETERMINING ESTUARINE FLOW REQUIREMENTS, AN SOUTH AFRICAN APPROACH

**Problem:** *Estuaries functions as an integrated ecosystem with a number key processes – physical (e.g. flushing, mixing and sedimentation), geochemical (e.g. flocculation), biochemical (e.g. remineralisation) and biological (e.g. primary production) – occurring at various temporal and spatial scales, which interactively drives the condition, or state, of the system. The differences in the scales at which the various processes function, make it very difficult to extrapolate the findings from one estuary to another without a substantial amount of measured, or modeled, data to describe the possible range of interactions occurring under different flow scenarios.*

**Response:** *Development of the concept of “Abiotic State” to assist with the linking of hydrodynamic and water quality characteristics under various flow regimes to form an integrated picture. A simplified model of the physical states (primarily controlled by hydrological characteristics) forms the basis of qualitative model, where physical processes and there resultant water quality conditions are defined for example in terms of characteristic salinity of the water column, flushing time and the mouth condition. Four primary physical states were identified: a freshwater-dominated state, freshwater pulsed/recovery state, marine-dominated state and the closed mouth state (Taljaard; van Niekerk and Joubert, 2009; Taljaard et al., 2009; Whitfield et al., 2008). This approach is applied in both data poor and data rich systems.*

South Africa has developed a method that relies on standard engineering approaches and scientific understanding and can be applied at various confidence levels. The method were specifically developed for data poor environments and had to be applicable at various levels of data availability, e.g. high confidence detailed studies for large dams versus low confidence, low accuracy for pre-feasibility or regional planning level studies. This method has been applied to over 25 detail studies and once-off on a national level (Van Niekerk and Turpie, 2012). Similar to the ELOHA the Method SA is a “top down” method for determining environmental flows and defines environmental flows in terms of acceptable levels of change from the natural flow regime (Arthington et al., 1998).

This chapter sets out to define the steps involved in determining environmental flows requirements for South Africa’s estuaries from an ecohydrological perspective, focusing on how you link the hydrological cycle to biological responses.

The South African method comprises four basic steps:

- 1) Describing the catchment and generating a long-term hydrological record;
- 2) Define the Abiotic States (identifying the physical conditions that occur predominantly in a specific estuary);
- 3) Identifying changes that have occurred in the Abiotic states or dominate physical conditions; and
- 4) Predicting biotic responses to these changes.

This section will mainly focus on describing step one to three. While this section will use South African examples to explain the application of the method the approach is generic and could equally well be applied in other regions of the world. In fact some of the subcomponents of the approach is international best practice and incorporated into some of the international approaches highlighted in Section 4, e.g. numerical modeling to understand the dominate physical conditions in an estuary (Pierson et al., 2003).

## 9.1 DESCRIBE CATCHMENT AND GENERATE SIMULATED HYDROLOGICAL RECORD

### 9.1.1 DESCRIBE THE CATCHMENT CHARACTERISTICS

Details on the catchment is necessary to understand some of the critical drivers influencing modifications in estuaries originating in the catchment, such as land-uses practices, wastewater discharges, water abstraction and the influence of dams. A description of the catchment provides an overview of the large scale (“far field”) pressures on the estuary and helps to identify some of the key issues that need to be addresses as part of a flow requirement or health assessment study.

The description of the catchment should include the following: size and geomorphological characteristics (e.g. influencing the biogeochemistry and sediment loads into estuary); details on the larger tributaries if need be (e.g. rainfall regime and seasonality); dominant land-use practices, including urban development, forestry, agriculture; details on water abstraction and the size and number of dams (including farm dams); wastewater discharges; mining activities (e.g. sand mining) and inter-basin transfer schemes.

The main drivers of changes in health can be grouped into two main categories, namely modification in river inflow (in terms of water volume, water quality and sediment supply) and anthropogenic influences other than flow modification.

In the South African method the present health of an estuary is expressed as the degree of similarity between the natural conditions and the present state. Likewise the future health of an estuary is estimated as the degree of similarity between the natural conditions and a projected future state.

In order to ‘hind-cast’ a Reference Condition or ‘forecast’ a future state, flow modification and other anthropogenic influences are key consideration. It is therefore important that such factors be identified and their influence on the estuary quantified as best possible.

### 9.1.2 GENERATE HYDROLOGICAL RECORD

Decisions cannot be made without information, but measured streamflow is often quite scares in South Africa due to sparse observation networks and lack of appreciation of the need for good data.

Rainfall-runoff models typically require as input data are measured rainfall and evaporation demand data. Parameters are used to represent the way in which a specific catchment responds to climate inputs. These parameters are be related to topography, vegetation cover, soils, geology and other natural catchment characteristics. In developed catchments, it is also necessary to consider all artificial impacts such as small and large dams, land use and water abstractions.

Using standardized hydrological methods generate a hydrological flow sequence based on rainfall and other known catchment parameters. The following information underpins a sound hydrological study:

measured rainfall data in the catchment (or in a representative adjacent catchment); measured stream flow data; verified hydrological parameters (e.g. evaporation rates, radiation rates); catchment size delineation; and reasonable estimation of stream flow losses (e.g. abstraction, impoundment) and gains (e.g. discharges, transfer schemes) from the system.

The hydrological sequence needs to be as long as possible, no less than 50 years to capture variability in inflow. The greater the natural variability in flow in a region, the longer the simulated record needs to be. This aspect is especially important in dry, temperate regions or monsoonal type systems where there is significant variability between seasons and years. In bimodal or equatorial rainfall areas where runoff is more evenly spread throughout the year it might be less important to capture such a long period of simulated runoff data as the variability is less and the sensitivity to flow would be easier to predict.

As the estuary responds to flow in all its variability, all components of flow need to be included, from floods to seasonal base flows. In addition, all operational rules for impoundments, abstractions and discharges also need to be aggregated into the flow sequence to provide a long term picture of past and present variability.

There are a number of hydrological models currently in use in South Africa and while the method is not prescriptive in which one can, or should be used, it is important to realise that from an environmental flows perspective, **base flows are a critical element (especially during the low flow period as this drives salinity penetration and mouth conditions)**. Some hydrological models (e.g. such as WR90 and WR2005) are often not capable of predicting base flows accurately, especially if no effort is made to refine the low flow component of the flow sequence. The simulated data should be as realistic as possible and include diversions of flow, operation rules of impoundments, and discharges from catchment and treatment works.

Experience has shown that hydrological models that can simulate the yield from a catchment provide the best results in this regard. This data is provided in the format of simulated monthly or daily flows, generated by a stochastic hydrological model from measured rainfall data in the catchment (or in a representative adjacent catchment).

Where a sufficiently long record of measured flow exists (> 50 years), you can compare the flow before and after the water resource development, but often this hides the effects of incremental water resource development, e.g. small scale run-of-river abstractions and farm dams. A more accurate method is to simulate the flow sequence for the present day – calibrated against known variables – and hind cast what flow would have been for the same period before significant catchment development (i.e. 100-200 year ago). Similarly flow sequence can also be generated for any future development of water resource, e.g. land-use change such as forestry or major impoundments.

### 9.1.3 STATISTICAL INTERROGATION

Finally the simulated flow sequence needs to be statistically interrogated to provide an indication, descriptive or statistically, of change in the flow regime focusing on (Olden and Poff, 2003):

- a) the magnitude of flow events (low and high flows);
- b) the frequency of flow events (low and high flows);
- c) the duration of flow events;
- d) the timing of flow events (seasonality); and
- e) the rate of change.

These analyses can be done on either monthly or daily flow sequences (Olden and Poff, 2003). Most South African studies have been done at the monthly time scales. Table 9.1 provides a summary of the more promising indicator of hydrological change.

Table 9.1 Potential indices of hydrological change that can be applied to SA catchments

Magnitude	Frequency	Duration	Timing	Rate of Change
<ul style="list-style-type: none"> <li>• Mean monthly/annual flows</li> <li>• Variability in monthly flows Coefficient of variation in daily/monthly flows</li> <li>• Skewness in daily/monthly/annual flows</li> <li>• Mean minimum / maximum monthly flows</li> <li>• Median of annual maximum flows</li> <li>• Variability across annual maximum flows</li> </ul>	<ul style="list-style-type: none"> <li>• Low flood pulse count</li> <li>• Frequency of low flow spells</li> <li>• Mean number of high flow events per year</li> </ul>	<ul style="list-style-type: none"> <li>• Mean magnitude of flows exceeded 75% and 90% of the time (calculated from the flow duration curve) divided by median daily flow, respectively, over all years)</li> <li>• Variability in number of zero-flow days</li> <li>• Percent of zero-flow months</li> <li>• Flood duration 1 Monthly flow equaled or exceeded 95% of the time divided by mean monthly flow</li> </ul>	<ul style="list-style-type: none"> <li>• Predictability of flow</li> <li>• Seasonality of flooding/low flows</li> </ul>	<ul style="list-style-type: none"> <li>• Rise rate</li> <li>• Fall rate</li> <li>• Reversals (Number of negative and positive changes in water conditions from one day to the next.</li> </ul>

With regards to magnitude of flow events, flood hydrographs should be provided at the head of the estuary for the 1:1 to 1:200 year floods. This information should be provided as a volume (million m<sup>3</sup>) and a maximum flow rate (m<sup>3</sup>/s). In high confidence studies the underlying simulated data used to estimate the flood events should be provided as a flow rate (m<sup>3</sup>/s) in hourly time steps.

The analyses of the typical flow ranges, and how they have or could change in future, assist in determining the typical physical conditions or abiotic states that dominate a specific estuary. As most flow requirements studies are constraint in time and budget the method requires that the most efforts should go into understanding the dominant or biologically important states.

## 9.2 IDENTIFY ABIOTIC STATES

This step requires the interrogation of measured (or modeled) data on hydrodynamic and geochemical process to identify typical physical or abiotic states occurring in the system and linking these states to representative flow ranges. As estuaries have a “memory”, i.e. temporal scales, abiotic states may need to be broken down into progressive states, i.e. closed mouth marine That progresses over time to closed mouth hypersaline.

Hydrodynamics, together with sediment and biochemical processes (i.e. the abiotic components) in estuaries are, in most instances, the ecological components where modification in flow and several other anthropogenic factors manifests its influences first. For example, reduced river inflow changes water circulation and salinity distribution patterns in estuaries that affect the biota or wastewater discharges affect the water chemistry of an estuary that affects the biota. Exceptions, which may have direct effects on biota, include influences such as living resource exploitation and human disturbance of biota. Knowledge and understanding of these abiotic components, therefore, are crucial in any flow requirement study in estuaries.

Estuaries receive water from two sources, i.e. the river and sea, each with distinctively different water quality characteristics, particularly in terms of system variables and nutrients. In turn, the water quality characteristics along the length of an estuary depends on the extent of the influences of each of these sources (governed by hydrodynamic processes), as well as biochemical processes (e.g. organic degradation, eutrophication) taking place at that point within the estuary. The influence of biochemical processes is particularly evident in parts of an estuary where residence time of water becomes longer, often observed along the middle reaches of an estuary during the low flow season.

Data requirements (see Appendix B for more detail) include continuous river inflow records; continuous water level recordings; daily mouth observations (in the case of temporarily open estuaries); wave conditions; historical aerial photographs and satellite imagery. Water quality data is require along the length of the estuary on salinity and temperature; system variables (pH, DO, turbidity, suspended solids and Secchi depth); inorganic nutrients (nitrate/nitrite, ammonia, reactive phosphate, total phosphorus and reactive silicate), suspended particulate organic matter. In addition water quality parameters should also be collected on of river inflow, to be sampled just upstream of the head of the estuary and the near-shore marine waters. In addition information should be gathered on effluent discharges and toxic substances to provide context to the flow related changes.

Because river inflow into an estuary, generally shows strong correlation with certain abiotic features and parameters, such as state of the mouth and longitudinal salinity distribution patterns, it is usually possible, for a particular estuary, to link or correlate river inflow ranges to typical ‘abiotic states’. Typical ‘abiotic states’, therefore, need to be determined for a particular estuary linking it to typical river inflow patterns.

The abiotic states for an estuary are primarily controlled by hydrological characteristics, i.e. river inflow. The approach followed here is to analyse the hydrological data provided for the system and to identify typical flow distribution ranges. For each of the selected flow ranges, physical characteristics need to be defined in terms of salinity-induced stratification of the water column, flushing time and the mouth condition, based on the understanding gained in the baseline studies (hydrodynamics). Further the biogeochemical characteristics of each state are then derived, gained in the baseline studies (water quality).

Taljaard et al. (2009) demonstrated a simplified model for the identification of such abiotic states. In their model they defined four dominant abiotic (or physical) states for South African estuaries: a freshwater-dominated state, freshwater pulsed/recovery state, marine-dominated state and the closed mouth state. However, in a specific application the range of states for a specific estuary may require further refinement within one or more of the dominant states, e.g. moderate marine-dominated and a strongly marine-dominated. The model is Van Niekerk et al., 2010

This step requires that the typical hydrodynamic and geochemistry conditions (referred to as abiotic states) that occur in an estuary under different flow ranges be describe in terms of: state of the mouth, flood plain inundation patterns, amplitude of tidal variation (indicative of exposure of intertidal areas during low tide); retention times of water masses, total volume and/or estimated volume of different salinity ranges, estimated (maximum) tidal velocities along the estuary, salinity distributions in the estuary, system variables (Temperature, pH, suspended solids, turbidity and dissolved oxygen) and nutrients (e.g. DIN, DIP and DRS). An example of the format in which the physical and biogeochemical characteristics of the defined abiotic states can be depicted is illustrated in Figure 9.2.

Longitudinal salinity contour plots are used to demonstrate salinity distribution patterns, while mixing diagrams (or property-salinity plots) – widely used to assess water column nutrient dynamics in estuaries – are used to describe inorganic nutrient distribution patterns. Nutrient concentrations are plotted against salinity along the estuarine gradient, providing a convenient method for displaying the net effect of nutrient processes within estuaries. For example, a linear relationship in the mixing diagram typically reflects straight mixing of the two water sources (i.e. the river and the sea), while downward curvature implies in situ nutrient uptake and upward curvature in situ nutrient release. Conservative behavior tends to occur during high river inflow, when estuaries are rapidly flushed. High nutrient input from the catchment (relative to input from the sea) reveals a negative linear correlation, whereas high input from the sea shows a positive linear correlation.

Deviation from the conservative mixing line tends to occur during periods of lower no river inflow, when long flushing times allow in situ processes to have a more significant influence on nutrient dynamics (e.g. remineralisation releasing nutrients into the water column or primary production taking up nutrients from the water column) (Taljaard et al., 2009).

Where there is not enough data numerical modeling can be used to simulate responses to flow. Methods that can be applied in assessing the hydrodynamics (or water circulation patterns) are numerous. These range from 3D numerical modeling, 2D numerical modeling, 1D numerical modeling, water balance models, statistical analysis or merely conceptual modeling (Van Ballegooyen et al., 2004).

Figure 9-1 Summary of typical physical and water quality characteristics of different abiotic states in the Palmiet Estuary (DWAF, 2010)

PARAMETER	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5
River flow (m <sup>3</sup> s <sup>-1</sup> )	< 0.05	Usually when flows < 1 (refer to Table 3.5)	1-10	10-20	> 20
Mouth condition	Closed	Semi-closed	Open (with extensive sea water intrusion)	Open (with limited seawater intrusion on the flood tide and strong river influence)	Open (with no seawater intrusion and very strong river influence)
Water level variation	None	None	0.3 m (could drop up to 0,5 m lower during low tide after freshet)	0.3 m (could drop up to 0,5 m lower during low tide after freshet)	Backing up effect
Inundation	Limited inundated	Intertidal area inundated	None	None	Intertidal and Floodplain inundated during peak flows
Circulation	Wind mixing	Entrainment	Tidal	Freshwater flushing and Tidal	Freshwater flushing
Salinity (psu)*	After storm 15 15 30 30 or 5 5 5 10 After state 2	< 1 month 15 15 20 25 or 5 5 5 15 > 1 month	20 15 35 30	0 0 25 10	0 0 0 0
Temperature (°C)	8-26 (usually summer)	18-26 (usually summer)	12-26 (usually summer, lower range saline waters during occasional upwelling)	12-17 (usually winter)	13-15 (usually winter)
pH	7-8	7-8	7-8	<6-8	< 6
DO (mg.l <sup>-1</sup> )	>6 2-6 >6 <2	Reference >6 2-6 <2 or >6 2-6 2-6 Present, persists >2 months	>6 >6 >6 >6	>6 >6 >6 >6	>6 >6 >6 >6
Transparency** (Secchi depth in m)	1-2 1-2 1-2	1-2 1-2 1-2 1-2	>2 >2 1-2 >2	1-2 1-2 1-2 1-2	1-2 1-2 1-2 1-2

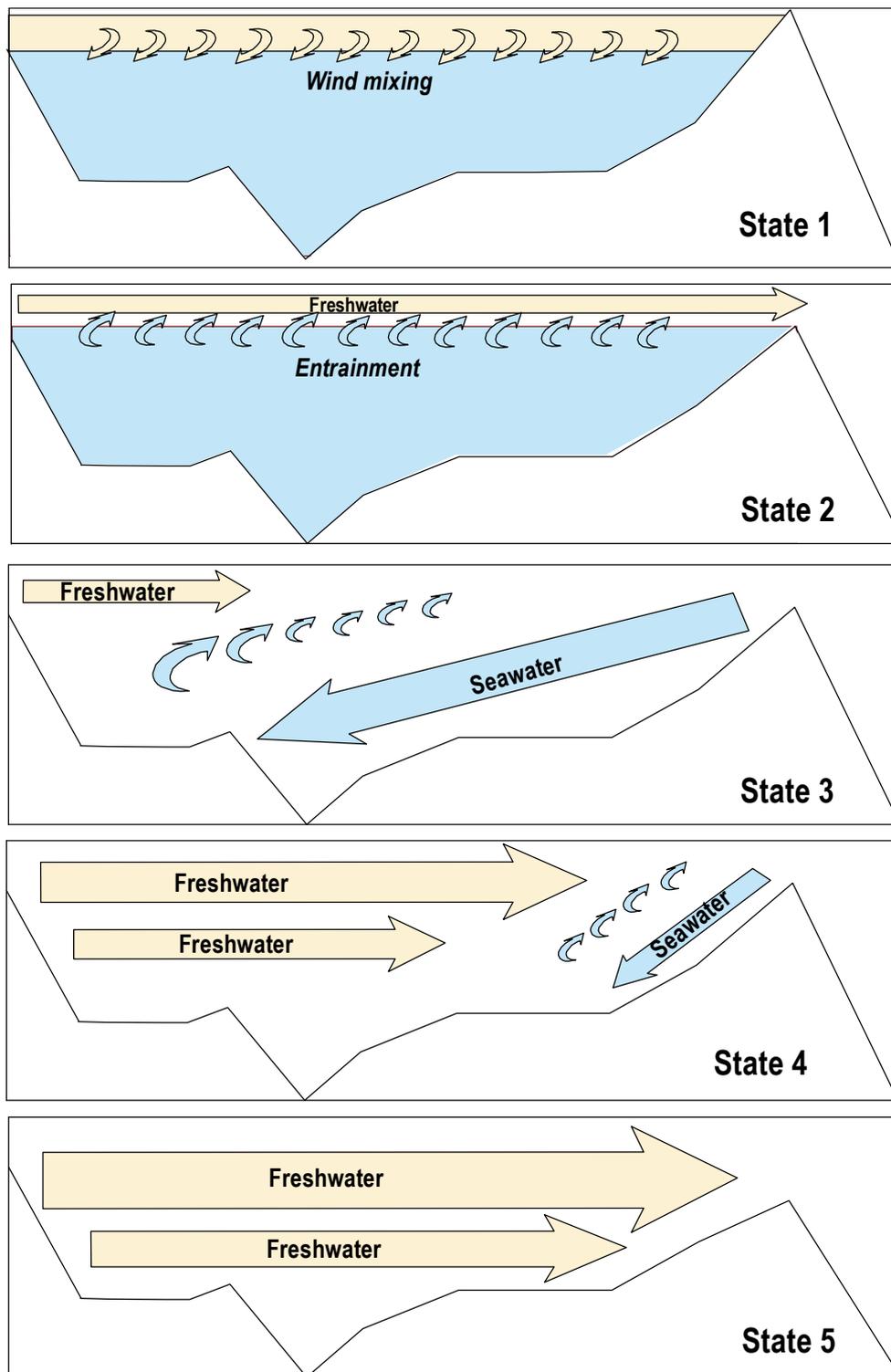


Figure 9-2 Schematic representation of the key circulation features of the five abiotic states of the Palmiet Estuary (after Van Ballegooyen et al., 2004)

A simple decision tree for application of numerical modeling is provided Van Ballegooyen et al. (2004). Numerical modeling is especially important in permanently open estuaries where the incremental effects of changes in river inflow are very difficult to derive from a number of once-off sampling surveys. Where funding is restricted or the study is of low confidence (e.g. pre-feasibility) the size and shape (bathymetry) can be used as a proxy for responsiveness to flow.

Abiotic States can also be hypothetical, where simulated flow data indicate a significant reduction or increase in flow ranges above the current inflow pattern, models (numerical or conceptual) can be used to predict and describe the physical properties of a abiotic state that could occur under predicted inflow conditions. An example is hypesaline condition that may start occurring for the first time under predicted low flow conditions.

### 9.3 IDENTIFY CHANGES IN ABIOTIC STATES

Once typical states have been identified and correlated with flow ranges that drives the state, these states are superimposed on the long term flow sequence for the various water development scenarios, ranging from Present, past to future. In its most simplified form changes can be represented by the difference in the % occurrence of the abiotic states over the modeled 50-70 year period.

Table 9.2. Example of estimated monthly flows and occurrence and duration of different abiotic states for the Palmet Estuary under the Present State flow scenario

YEAR	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1928	2.41	0.96	0.70	0.52	0.52	0.26	1.52	2.72	3.39	10.94	12.33	6.11
1929	1.24	0.73	0.52	0.39	0.47	0.50	0.48	0.53	1.36	2.73	5.79	13.43
1930	6.50	1.81	0.78	0.31	0.34	0.28	2.67	3.36	2.00	5.84	15.72	13.32
1931	11.21	2.07	0.70	0.46	0.86	0.55	0.33	3.18	7.72	9.88	8.39	13.22
1932	5.90	1.07	0.51	0.33	0.31	0.29	0.32	1.43	10.09	12.23	18.19	6.36
1933	2.84	0.97	0.39	0.26	0.33	0.32	0.30	1.57	2.13	4.44	10.70	8.98
1934	8.51	1.99	0.52	0.27	0.27	0.48	1.32	4.35	5.92	6.76	5.60	6.03
...												
...												
...												
1991	8.41	2.50	0.68	0.52	0.37	0.33	2.07	7.72	24.39	21.29	14.83	12.88
1992	17.14	3.42	0.66	0.52	0.74	0.28	11.40	7.68	12.89	47.18	16.40	5.25
1993	1.22	0.53	0.83	0.10	0.06	0.19	0.33	1.37	20.07	13.50	10.03	4.57
1994	2.83	0.73	0.37	0.22	0.17	0.14	0.48	2.92	8.07	12.63	16.33	5.29
1995	9.19	2.39	3.29	1.17	0.54	0.52	0.52	2.23	9.02	15.00	14.16	19.16
1996	22.68	8.72	2.63	0.80	0.52	0.63	0.94	3.12	15.65	8.99	12.32	4.89
1997	1.21	5.36	1.50	0.57	0.52	0.25	1.08	8.77	9.08	13.08	10.22	4.35
1998	1.54	5.40	2.06	0.76	0.52	0.52	0.71	2.60	6.40	8.51	10.14	9.93
1999	3.64	1.07	0.39	0.47	0.09	0.71	0.40	1.77	5.22	6.65	8.57	12.16
2000	2.71	0.91	0.54	0.26	0.39	0.16	0.29	5.71	4.75	22.35	26.07	23.23
2001	2.88	1.35	0.65	1.82	0.79	0.52	1.63	3.70	8.30	11.56	16.31	5.15
2002	4.74	1.47	0.44	0.32	0.29	1.12	0.78	3.14	3.55	3.08	10.83	6.02
2003	4.71	1.11	0.60	0.48	0.24	0.27	0.22	0.75	3.81	6.47	9.41	4.80
2004	6.26	1.63	0.49	0.35	0.27	0.16	4.87	5.31	13.81	7.91	16.72	6.33

State 1	<0.15	State 2	0.15-1	State 3	1-10	State 4	10-20	State 5	> 20
---------	-------	---------	--------	---------	------	---------	-------	---------	------

Table 9.3. Example of summary of monthly flows and occurrence and duration of different abiotic states for the Palmet Estuary under the Present State flow scenario

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
99%ile	20.44	8.79	3.58	2.81	2.35	2.44	6.71	12.85	25.58	43.56	36.36	27.49
90%ile	11.40	3.90	1.43	0.82	0.83	1.05	3.53	7.91	19.69	23.38	26.15	18.69
80%ile	6.84	2.52	0.86	0.57	0.68	0.81	2.06	5.38	12.63	17.56	20.33	13.41
70%ile	5.89	1.98	0.74	0.52	0.54	0.57	1.50	4.34	9.39	13.56	16.77	12.18
60%ile	4.52	1.66	0.67	0.52	0.52	0.52	1.19	3.78	8.25	11.61	16.08	9.89
50%ile	3.66	1.47	0.60	0.52	0.50	0.44	0.97	3.12	7.03	9.91	13.54	8.30
40%ile	3.17	1.36	0.56	0.46	0.34	0.33	0.74	2.56	5.46	8.88	11.20	6.70
30%ile	2.81	1.20	0.54	0.35	0.32	0.30	0.57	2.13	4.14	6.74	9.94	6.10
20%ile	2.40	1.00	0.52	0.32	0.29	0.27	0.48	1.61	3.57	5.43	8.64	5.67
10%ile	1.82	0.89	0.44	0.28	0.26	0.25	0.33	1.33	2.56	4.63	7.23	5.05
1%ile	1.22	0.61	0.33	0.10	0.08	0.12	0.25	0.70	1.32	3.00	5.02	3.95

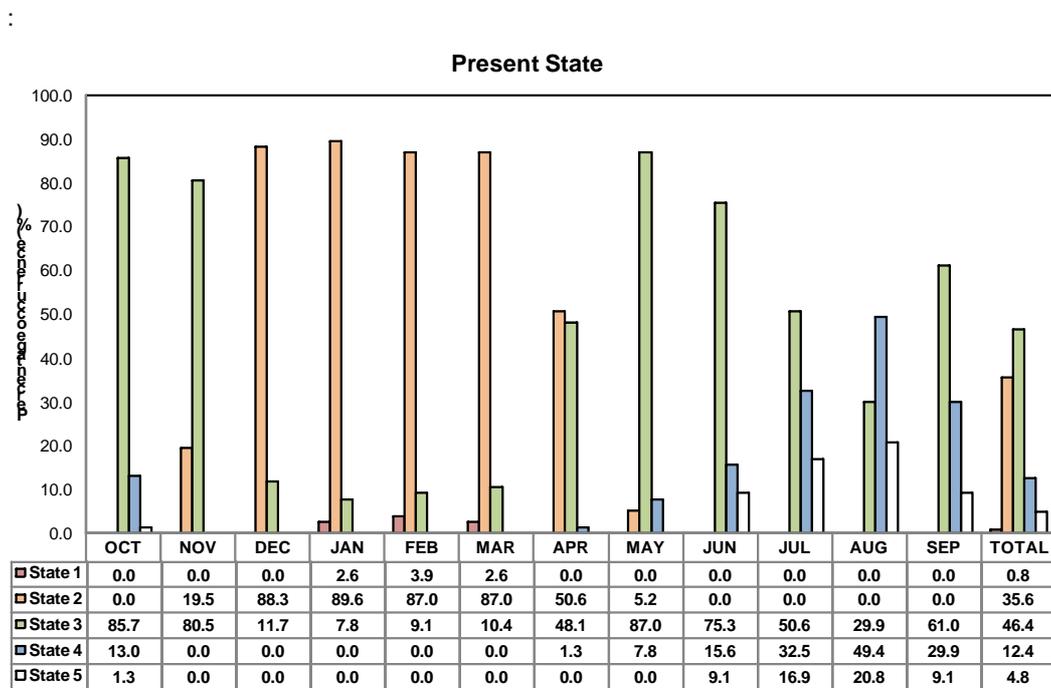


Figure 9-3: Option for summarising the seasonal distribution of flows, particularly for estuaries where variations within months are stronger than seasonal variation

#### 9.4 PREDICT CHANGES THE BIOTIC COMPONENTS OF THE ESTUARINE ECOSYSTEM

Linked ecological responses to Abiotic States using measured field data on specific system or known tolerance ranges to abiotic drivers. While salinity is the main factor most biotic component calibrate against aspects such as temperature, oxygen, turbidity, nutrients and pH may well drive significant

predictable responses. Biotic components such as fish can then predict their responses to flow based on the predicted change in Abiotic States and not flow per se. It might be necessary to develop hypothetical responses, based on known tolerances of states that have not been recorded in the estuary before.

The biotic components are required to be provided measured, modeled or predicted responses for the various biological components (microalgae, plants, invertebrates, fish and birds for species richness, abundance, community composition. More detail on the biological prediction process is provided in Adams *et al.* (2003) and Lamberth *et al.* (2009).

## 9.5 SEDIMENT PROCESSES

The disturbance of the sediment erosion/deposition equilibrium in an estuary can lead either to siltation, resulting in the estuary becoming shallower, or it can lead to the erosion of important sediment habitats. Under natural conditions many estuaries were probably in a state of long-term equilibrium of sedimentation and erosion. However, this equilibrium can be disturbed because of changes in run-off, especially if the occurrences and magnitudes of major floods are changed. Floods and, in some cases, high seasonal flows can influence the sediment erosion/deposition equilibrium. Floods can alter important features within an estuary, such as the bathymetry (e.g. channel depth or the size of intertidal areas) and sediment composition (e.g. sand or mud).

The abiotic state approach do not capture aspects relating to structural habitat change (supratidal, intertidal or subtidal). Sediment process are predominantly driven by larger flow events, i.e. 1: 10 years. These responses can be derived from measured data (cross sections difference before and after a flood) or from numerical modeling studies. Once again the changes in sediment process can be superimposed on the longer hydrological sequence to show changes in inundation patterns and resetting events. Only aspects relating to mouth state, tidal variation, water levels and retention are addressed intrinsically and is predetermined for by the Abiotic state approach. Similarly change in inundation of flood plains can be predetermined by numerical modeling and linked back to typical monthly flows representative of these inundation patterns. Recognizing that if there is significant changes in the magnitude of flow, monthly sequences will be unresponsive and hide such change.

Sediment samples (grab and cores); topographical and bathymetric data; and estimates of the sediment load in the inflowing water are required to describe the sediment distribution and dynamics of an estuary. Particularly if numerical hydrodynamic modeling is to be used in estimating natural condition and the implication of future scenarios. Note: It may not be possible to acquire these data sets in the short term, but long term monitoring programmes to collect such data must be considered if the dynamic sediment processes in estuaries are to be better understood. Typically, 2D numerical models have been applied to assess sediment processes in South Africa estuaries.

The description of the sediment processes in an estuary primarily characterizes the physical and structural habitat. This is achieved through describing the sediment distribution (e.g. mud/sand ratios), as well as the major factors influencing the sub-tidal, intertidal, supra-tidal and floodplain habitat.

Studies can take place without these measurements, based on expert opinion and preferably a site visit. Sediment samples are relatively straightforward, but the confidence will be most positively affected by bathymetry. Historical data on sedimentation and erosion processes over 15 years or more will help to understand the impacts of changes in larger floods (e.g. >1:5 year floods). To really understand sediment loads, one needs to have daily data, preferably over a long time period of up to

5 years. This is seldom available unless the study is planned for well in advance. Confidence can also be increased by numerical modeling.

## 9.6 DISCUSSION

### 9.6.1 SCALES

The method can be applied at any temporal or spatial scale. In South Africa long river inflow sequences are typically simulated in monthly time steps. Most hydrological models are geared towards that. Daily flow sequences are available but normally at shorter interval, e.g. 20 years, which is comparable with the South African wet/dry cycle.

Monthly flow data are appropriate for larger catchments where seasonal base flows responds on monthly time frames and floods mostly occur at weekly scales. Especially where such inflows end up in a large estuary where signals from flood pulses remain in the system for weeks to months at a time. Daily inflows may be more appropriate in the case of smaller catchments where flows and flood peaks occur at shorter time scales – hours to days – especially where such inflow flow into small estuary with little retention capacity which in turn leads to little memory to higher flows. Low baseflows in the dry season would still operate and daily to weekly scales with some aggregation of water quality variables.

Small to medium catchment with very erratic flow patterns also functions at daily to weekly time scales while larger estuaries tend to have some retention, therefore the assessment might need to be done at a weekly time step. In South Africa at present flow requirements studies are still assessed against monthly flow sequences, but in the case of small to medium catchments that tends towards more erratic flows, abiotic states are predicted as occurring within the month versus being there the entire period.

### 9.6.2 EFFECTS OF DATA ON CONFIDENCE

Confidence in the hydrodynamics description and predictions is highly dependent on long-term data sets. Continuous flow data are crucial for correlating river flow to the state of the mouth (as reflected by water level recordings), particularly in temporarily open/closed estuaries. The dataset duration required will depend on, for example, the frequency of mouth closure in the particular estuary. About five years of data is needed for medium confidence and up to 15 years for high confidence. Water and sediment quality data are particularly important for interpretation of specific biological responses and, therefore must be collected by the relevant biotic components as indicated during their sampling surveys.

## 9.7 ANTHROPOGENIC INFLUENCE

The method also require the description of non-flow related anthropogenic influences on abiotic components and processes within estuary to determine how they affect hydrodynamics and water quality in the estuary and how. A checklist for activities relating to land-use and development practices and water quantity and quality relate issues and is provided to give guidance:

Land-use and development	Water Quality and Quantity
<ul style="list-style-type: none"> <li>• Artificial breaching</li> <li>• Mouth stabilization</li> <li>• Bank stabilization &amp; destabilization</li> <li>• Bridge(s)</li> <li>• Weirs</li> <li>• Causeway</li> <li>• Marina development</li> <li>• Dredging</li> <li>• Mining (e.g. sand winning)</li> <li>• Poor agricultural practices (e.g. causing siltation)</li> <li>• Exceedance of carrying capacity resulting from boating, bathers, etc.</li> <li>• Low-lying developments</li> <li>• Lack of maintenance of infrastructure (e.g. roads and bridges)</li> <li>• Migration barrier in river</li> </ul>	<ul style="list-style-type: none"> <li>• Waste water treatment works</li> <li>• Municipal waste (including sewage disposal)</li> <li>• Industrial effluent (including cooling water) discharges</li> <li>• Litter</li> <li>• Mari culture waste products</li> <li>• Pollution related to shipping activities in harbours</li> <li>• Septic and conservancy tank seepage</li> <li>• Agricultural and pastoral run-off containing fertilisers, pesticides and herbicides</li> <li>• The inflow of contaminated storm-water or groundwater</li> <li>• Lack of maintenance of infrastructure (e.g. sewage works)</li> </ul>

## 10. PRINCIPALS OF ESTUARINE ENVIRONMENTAL FLOWS REQUIREMENTS STUDIES

This section highlights some of the key principals underlying environmental flows requirements to estuaries.

### **Principle 1: “That estuaries responded to flow in all its variability”.**

River flow in all its variability is the primary driver of estuary condition. All components of flow contribute to the current state of an estuary. If river inflow is modified it will have some resultant response in estuarine processes and functioning, it is just the scale of the response that is in question.

This distinguishes the estuaries method from the rivers method which tends to build its flow requirements or request specific flow events to achieve a desired state. Estuaries, because of the memory effect, required a more integrative approach. This principle requires an evaluation of hydrology *per se* to reflect the change in the driver. Hydrology also serves as a proxy for all the components as the current EFR method do not evaluate all aspects of the ecosystem, e.g. bacteria, mammals, amphibians.

This principle is also embraced in more recent work coming from the field of ecohydrology that emphasizes that changes in flow in all its variability should be reflected (Poff).

### **Principle 2: “An ecosystem based approach is required to deal with the complex nature of estuaries”**

The method follows an ecosystem approach. The method assumes that all components of an estuary ecosystem are interconnected. The method therefore does not just look at a few key processes, niches or species, e.g. flow (e.g. percentage of flow approach) or fish (e.g. changes in abundance or species richness) as indicator of condition.

This principal is also reflected in the fact that all nine components (abiotic and biotic) are evaluated regardless of the scale of the impact. What may vary though is the level of assessment depending on the degree of flow modification and the sensitivity of the water resource.

The ecosystem based approach to EFR contrast with risk assessment methods that would generally allow for an initial evaluation of the ecosystem drivers (i.e. flow, hydrodynamics and water quality) and assume that the ecosystem will remain in the same condition as long as the abiotic drivers are intact.

### **Principle 3: “Estuaries follow a precautionary approach”.**

This principle is for example reflected in the fact that the Biotic Components takes the minimum score of species richness, abundance and community composition.

While this same principal is not explicitly embedded in the Abiotic components scoring system, as this part of the Estuary Health Index average or use set weightings, but flow bands related to mouth closure and salinity penetration are taken conservatively in the absence of real data.

This principal also comes to play especially in the case of Rapids (and desktop) assessments where little information is available and expert opinion drives the process with a requirement to be explicit about assumptions and confidence.

**Principle 4: Estuaries EWR method focuses on the needs of the ecosystem, with the social and economic issues being dealt with explicitly and separately as part of the larger RDM process external to the ecological assessment.**

While the estuary ecological assessments methods require realist planning scenarios to derive at the recommend EFR is should not be concerned with the opportunity cost to water resources managers or development of the catchment resources. The operational landscape of water resource management is constantly changing – very sensitive to climate cycles (drought), currency fluctuations (can afford a pipe line or not) and regional politics – and can date the findings of a study relatively quickly if not seen more holistically.

Separating the ecological assessment from the socio-economic aspects allows for the most realistic ecological “bid” to be developed for the estuary. Thus, somewhat one sided view, in turn can then be tempered with the socio-economic requirements of the greater planning unit.

**Principle 5: Every estuary is unique**

Note, that although one standard method is applied to all the estuaries in South Africa it is adjusted from estuary to estuary to reflect change on an individual estuary basis.

This is primarily done through the abiotic state descriptions, but may also require a different aggregate of some of the other abiotic components, e.g. water levels and salinity in larger lakes systems are often require aggregation of annual temporal scales versus temporarily open/closed estuaries that change in monthly time scales.

The method must not be so prescriptive that it cannot accommodate a specific condition not previously encountered, for example accounting for semi-closed mouth conditions which is neither a closed mouth state nor a fully open condition.

**The challenge is to make sure that every EWR study reflects the story of the estuary it is assessing. The story is what is important; the method is merely the framework within which it is done.**

## 11. RECOMMENDATIONS FOR IMPROVEMENT OF THE ABIOTIC COMPONENT OF THE RDM METHODS

### 11.1 HYDROLOGY

#### Surface Hydrology

- The abiotic specialists need to understand what flow components are changing as it is not always possible to up front define what is ecologically significant. In small estuaries and/or data poor environments, it is often difficult to define the abiotic states with a high resolution, i.e. can only identify two or three abiotic states. Thus in turn, can hide the degree of change occurring in the system. The disaggregating of the changes in river inflow into the various components (i.e. frequency, magnitude, duration, seasonality and skewness) could provide the ecological assessment with additional insights not reflected in the overall summaries of the change in abiotic states.

#### Groundwater and seepage

- The groundwater input can be an important component of flow in small estuaries (e.g. Groen) or in systems that remain closed for long periods (e.g. St Lucia or Swartvlei). This information needs to be quantified in Intermediates and Comprehensive Reserves.
- Seepage losses through the sand berm at the mouth can be substantial (e.g. coarse grains beach with steep slope) and needs to be quantified more systematically through measurements and groundwater studies

#### Floods

- Estuary EFR studies need detailed information on the frequency and duration of floods (e.g. shape of curve). This must be provided by the hydrologist. Floods have two main functions in estuaries: Large events can reset sediment processes, but smaller events can reset the water column and some of the organic matter that accumulate over time in a system. While the roll of large events is relatively well understood, the importance of these intermediate type events is only beginning to emerge. This aspect needs urgent attention to assist with the integration of floods in the assessment methods.

### 11.2 HYDRODYNAMICS

#### Mouth closure

- Nothing replaces good data on mouth state, e.g. daily mouth observations and continuous water level data. The classic water balance model provides the best assessment tool for mouth conditions. This report highlights a number of approaches. One aspect that does require some additional work is the incorporation of the semi-closed mouth state as it represents both conditions of the closed state and the open state.

#### Retention time/Exposure time

- The hydrodynamics component of the study needs to explicitly address changes in retention /exposure time. Biota that are associated with the water column habitat respond to changes

in retention time (e.g. phytoplankton), while biota associated with benthic environment respond to exposure time, e.g. benthic microalgae. Both aspects need to be addressed in. Numerical modeling is the most accurate method for calculating the residence time for a range of possible flow condition. If sufficient information is available the sum of the total occurrence of an abiotic state can be multiplied by the average residence time per state and compared between scenarios to provide an indication of shifts in residence time.

#### **Water levels and volume changes**

- Changes in water level needs to be explicitly addressed as part of the EWR methods. The average water level or volume can be estimated by multiplying the average water level per state with the percentage occurrence of each abiotic state. Information on the size and shape (bathymetry) of individual system of individual system will be invaluable for this.

#### **Stratification**

- The degree of stratification per scenario can be estimated by multiplying the average degree of stratification per state with the percentage occurrence of each abiotic state. The degree of stratification can be expressed as the Richardson number or the amount of energy input needed to break down the stratification (Dyer, 1997; Simpson et al., 1990).

### **11.3 WATER QUALITY**

#### **Salinity**

- Estuary EWR studies must always provide some estimation of changes in salinity. This estimate must reflect both average salinity and seasonal salinity changes. The information should also be explicitly linked to a % change in surface area or volume.
- Numerical modeling is always required for EWR assessments in permanently open system to provide accurate evaluation to sensitivity to flow. The exceptions to this rule are places where long term data sets have been correlated with measured flow data.

## 12. REFERENCES

- Acreman M (2003). Defining water requirements. In: M. Dyson, G. Bergkamp, J Scanlon (Editors), Flow: The Essentials of Environmental Flows. IUCN, The World Conservation Union, Switzerland & U.K, pp. 11-28
- Adams JB, Bate GC, Harrison TD, Huizinga P, Taljaard S, van Niekerk L, Plumstead EE, Whitfield AK, Wooldridge TH (2002). A method to assess the freshwater inflow requirements of estuaries and application to the Mtata estuary, South Africa. *Estuaries* 25 (6B): 1382-1393.
- Allanson BR and Baird D eds (1999) Estuaries of South Africa. 340pp Cambridge: Cambridge University Press.
- Alber M and Flory J (2002). The effects of changing freshwater inflow to estuaries: A Georgia perspective. Georgia Coastal Research Council, State of Georgia, 53 pp. [www.gcrc.uga.edu/FocusAreas/freshwater\\_inflow.htm](http://www.gcrc.uga.edu/FocusAreas/freshwater_inflow.htm)
- Alber M (2002). A conceptual model of estuarine freshwater inflow management. *Estuaries* 25, 1246-1261.
- Arthington AH, Brizga SO, Kennard MJ (1998). Comparative evaluation of environmental flow assessment techniques: best practice framework. LWRDC Occasional Paper 25/98. Land and Water Resources Research and Development Corporation LWRDC: Canberra; 26 pp.
- Arthington AH, Bunn SE, Poff NL, Naiman RJ, (2006). The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16, 1311-1318.
- Baird M, Walker S, Wallace B, Sakov P, Parslow J and Waring J (2001). Simple Estuarine Response Model. A coupled biological-physical model of estuarine response in Australian estuaries. CSIRO and CRC for Coastal Zone, Estuary and Waterway Management. National Land and Water Resources Audit. <http://www.per.marine.csiro.au/serm/>
- Bao, Y., Mays, L.W., (1994). Optimization of freshwater inflows to Lavaca-Tres Palacios, Texas, estuary. *Journal of Water Resources Planning and Management* 120, 218-236.
- Bate, G.C., Whitfield, A.K., Adams, J.B., Huizinga, P., Wooldridge, T.H., (2002). The importance of the river estuary interface (REI) zone in estuaries. *Water SA* 28, 271-279.
- Beck JS, Kemp A, Theron AK, Huizinga P, Basson GR (2004). Hydraulics of Estuarine Sediment Dynamics in South Africa: Implications for Estuarine Reserve Determination and the Development of Management Guidelines. *WRC Report 1257/1/04*
- Binnie, Black and Veatch Engineering Consultants. (1998), Determining The Freshwater Flow Needs of Estuaries, R & D Technical Report W113, September, Environment Agency, Bristol, ISBN SO-7/98-B-BAXV.
- Bishop KA (2005). Hastings District Water Supply Augmentation Scheme: detection of potential future water-extraction impacts on the aquatic biota of the lower Hastings River. Main Specific Monitoring Report. Study undertaken for the NSW Department of Commerce on behalf of the Hastings Municipal Council, March 2005.

- Bishop, K.A., Taylor, M., Cloke, P., Chadwick, M. (2001). Emigrant Creek Dam environmental flows investigation. Study undertaken for Rous County Council.
- Boyes B (2006). Environmental Water Requirements for the Shoalhaven River Estuary – Discussion Paper. Shoalhaven Environmental Flows Scientific Advisory Panel. NSW Department of Natural Resources, March.
- Brizga SO, Arthington AH, Choy SC, Kennard MJ, Mackay SJ, Pusey BJ, and Werren GL (2002). Benchmarking a ‘top-down’ methodology for assessing environmental flows in Australian Rivers. Proceedings Environmental Flows Conference, 4<sup>th</sup> Ecohydraulics conference 2002, Cape Town. [www.uiweb.uidaho.edu/ecohydraulics/.../Brizga/BrizgaSText.pdf](http://www.uiweb.uidaho.edu/ecohydraulics/.../Brizga/BrizgaSText.pdf)
- Brizga, S.O., Craigie, N.M., Arthington, A.H., Choy, S., McKay, S., Pusey, B., Werren, G., Poplawski, W., (2001d). Pioneer Valley Water Resource Plan: Proposed Environmental Flow Assessment Framework. Department of Natural Resources and Mines, Brisbane.
- Browder, J.A., Moore, D., (1981). A new approach to determining the quantitative relationship between fishery production and the flow of fresh water to estuaries. In: R. Cross, D. Williams (Editors), Proceedings of the National Symposium on Freshwater Inflow to Estuaries, FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C., pp. 403-430
- Close PG (2005). Information Requirements and a Recommended Procedure for the Determination of Ecological Water Requirements for the Hill and Moore River Estuaries. Centre of Excellence for Natural Resource Management, University of Western Australia. 84 pp.
- Close PG (2007). Water requirements for estuaries: relationships between freshwater inflows, hydrodynamics and larval fish dynamics in estuarine lagoons, south-western Australia. Ph.D. Thesis, University of Western Australia, Australia. 289 pp.
- Cooper JAG (2001). Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* 40, 99-122.
- Cox DR and Peirson WL (2003) Hawkesbury Nepean River saline dynamics long term model simulations. WRL Technical Report 2003/10. Study undertaken for the Hawkesbury Nepean River Forum. October 2003. [www.hawkesbury.nsw.gov.au/files/28299/File/Bill\\_Peirson.pdf](http://www.hawkesbury.nsw.gov.au/files/28299/File/Bill_Peirson.pdf)
- CSIR (1983). *Estuaries of the Cape Part II: Synopses of available information on individual systems* (A.E.F. Heydorn and J.R. Grindley, Eds.). Report No. 20: Groot Brak. (CMS 3) CSIR Research Report 419.
- CSIR (1990). Great Brak River estuary environmental study with reference to the requirements of the estuary and downstream users. CSIR Report EMA-C 9036. 248 pp. Stellenbosch, South Africa.
- CSIR (2000). Great Brak Estuary management programme. Report on the monitoring results for the period November 1999 to November 2000. *CSIR Report* ENV-S-C 2000-131. Stellenbosch.
- CSIR (2003). Great Brak Estuary management programme. Review Report March 2003. *CSIR Report* ENV-S-C-2003-092. Stellenbosch.

- Department of Water Affairs And Forestry (DWAF) (1999). Water resource protection and assessment policy implementation process. Volume 5: Resource directed measures for protection of water resources: estuarine ecosystems component. Report No. N\31\99. Pretoria.
- Department of Water Affairs and Forestry (DWAF) (2004b) Preliminary Determination of the Ecological Reserve on a Rapid Level for the St Lucia Estuary.
- Department of Water Affairs and Forestry (DWAF) (2007) Berg River Baseline Monitoring Programme Final Report – Volume 3: Estuary And Floodplain Environment. Clark, B.M & Ratcliffe G. (Eds). Report prepared for the Department of Water Affairs and Forestry, DWAF Report No. P WMA 19/G10/00/1907. Pretoria.
- Department of Water Affairs and Forestry (DWAF) (2008) Preliminary Determination of the Ecological Reserve on a Rapid Level for the Swartvlei Estuary.
- Department of Water Affairs and Forestry (DWAF) (2009) Preliminary Determination of the Ecological Reserve on a Intermediate Level for the Great Brak Estuary.
- Department of Water Affairs and Forestry (DWAF) 2007. Determination of the preliminary ecological reserve on a intermediate level for Mdloti Estuary. Final Report submitted to Directorate Resource Directed Measures, 2007. Pretoria: DWAF.
- Department of Water Affairs and Forestry (DWAF). 2004a. Thukela Water Project Decision Support Phase. Reserve Determination Model. Volume 1: Appendices to Thukela Estuarine Flow Requirements. PBV000-00-10307. Directorate of National Water Resource Planning. Pretoria: DWAF.
- Department of Water Affairs and Forestry (DWAF). 2004b. Water Quality Management Series Sub-Series No. MS 13.4. Operational policy for the disposal of land-derived water containing waste to the marine environment of South Africa – Appendices. Edition 1. Pretoria: DWAF. Available at [http://www.dwaf.gov.za/Dir\\_WQM/docs/marine/MarineWasteAppendicesOct04.pdf](http://www.dwaf.gov.za/Dir_WQM/docs/marine/MarineWasteAppendicesOct04.pdf) [accessed September 2010].
- Doering, PH, Chamberlain, RH, Haunert, DE (2002). Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee Estuary. *Estuaries* 25, 1343-1354.
- Dyson, M., Bergkamp, G., Scanlon, J. eds. 2003 *Flow: The Essentials of Environmental Flows*. pp 11-28. Switzerland & U.K., IUCN The World Conservation Union. 118 pp.
- Estevez, E.D., 2002. Review and assessment of biotic variables and analytical methods used in Estuarine Inflow studies. *Estuaries* 25, 1291-1303.
- Fijen AMP (1995). Swartvlei catchment, Diep, Klein-Wolwe, Hoëkraal and Karatara Rivers, water management strategy. Volume 3: Water quality. Department of Water Affairs and Forestry, Pretoria. 51 pp.
- Flannery, MS, Peebles, E, Montgomery, RT (2002). A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to Southwest Florida Estuaries. *Estuaries* 25, 1318-1332.

- Gillsanders BM and Kingsford MJ (2002). Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology: An Annual Review* 40, 233-309.
- Gippel CJ, Anderson B, Harty C, Bond N, Sherwood J, Pope A (2009). Gap analysis and strategy development for national level estuary environmental flows policies. Waterlines Report, National Water Commission, Canberra. [www.nwc.gov.au/resources/.../Waterlines\\_estuaries\\_final\\_report1.pdf](http://www.nwc.gov.au/resources/.../Waterlines_estuaries_final_report1.pdf)
- Groffman PM (2006). Ecological Thresholds: The Key to Successful Environmental Management or an Important Concept with No Practical Application?
- Halliday IA and Robins JB (2007) Environmental flows for subtropical estuaries: understanding the freshwater needs of estuaries for sustainable fisheries production and assessing the impacts of water regulation. Final Report FRDC Project NO. 2001/022 Coastal Zone Project FH3/AF.
- Halliday IA, Robins JB and Staunton-Smith JS (2003). A conceptual framework for investigating environmental flows for estuarine fisheries production. Paper presented at 2003 Riversymposium. <http://archive.riverfestival.com.au/2003/content/papers2003Index.htm>
- Hannah DM, Wood PJ and Sadler JP (2004) Ecohydrology and hydroecology: A new 'paradigm?' *Hydrological Processes* 18, 3439-3445.
- Hardie R, Lloyd L and Sherwood J (2006). Draft Method for Pilot Trials: Determining the Environmental Water Requirements of Victoria's Estuaries – Development of a Module to Extend the Flows Methodology, Earth Tech Engineering Pty Ltd, Australia. 1-101 pp.
- Hay D, Huizinga P, Mitchell S (2005). Managing sedimentary processes in South African estuaries: A guide. *WRC Report TT241/05*
- Hirji R and Panella T (2003). Evolving policy reforms and experiences for addressing downstream impacts in World Bank water resources projects. *River Research and Applications* 19, 667-681.
- Hollings, C.S., 1978. Adaptive Environmental Assessment and Management. John Wiley and Sons, New York.
- Huizinga P and van Niekerk L (2002). The Role of River Flow in Maintaining Physical Processes in South Africa's Estuaries. *Enviro Flows 2002. Proceedings of the International Conference on Environmental Flows for River Systems, incorporating the 4<sup>th</sup> International Ecohydraulics Symposium Proceedings*.
- Jezewski WA, Roberts CPR (1986). Estuarine and Lake Freshwater Requirements. *DWAF Technical Report TR129*
- Kennish, M.J., (2000). Introduction. In: M.J. Kennish (Editor), Estuary Restoration and Maintenance, The National Estuary Program. CRC press, Florida, pp. 1-7.
- Kimmerer, W. (2002) Physical, biological and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries* 25, 1275-1290.
- King J, Brown C and Sabet H 2003 A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* 19, 619-639.

- King J, Tharme R and Brown C 1999 Contributing Paper: Definition and Implementation of Instream flows. Thematic Report World Commission on Dams.
- King, J., Louw, D., (1998). Instream flow assessments for regulated rivers in South Africa using the
- Lamberth SJ & Turpie, JK (2003). The role of estuaries in South African fisheries: Economic importance and economic implications. *African Journal of Marine Science* 25: 131-157.
- Lamberth SJ, Drapeau L, Branch GM. 2009. The effects of altered freshwater inflows on catch rates of non-estuarine-dependent fish in a multispecies nearshore line-fishery. *Estuarine, Coastal and Shelf Science* 84: 527-538.
- Lamberth SJ, van Niekerk L and Hutchings K. (2008) Comparison of, and the effects of altered freshwater inflow on, fish assemblages of two contrasting South African estuaries: the cool-temperate Olifants and the warm-temperate Breede. *African Journal of Marine Science*, Volume 30, Number 2, September 2008 , pp. 311-336(26).
- Largier JL and Taljaard S (1991). The dynamics of tidal intrusion, retention, and removal of seawater in a bar-built estuary. *Estuarine, Coastal and Shelf Science* 33, 325-338.
- Lawrie RA and Stretch DD (2011a). Anthropogenic impacts on the water and salinity budgets of St Lucia estuarine lake in South Africa. *Estuarine, Coastal and Shelf Science* 93, 58-67.
- Lawrie, RA and Stretch, DD (2011b) Occurrence and persistence of water level/salinity states and the ecological impacts for St Lucia estuarine lake, South Africa. *Estuarine, Coastal and Shelf Science* 93, 58-67.
- Liu, W-C., Liu, S-Y., Hsu, M-H., Kuo, A.Y., (2005). Water quality modelling to determine minimum instream flow for fish survival in tidal rivers. *Journal of Environmental Management* 76, 293-308.
- Lloyd, L.N., Anderson, B.G., Cooling, M., Gippel, C.J., Pope, A., Sherwood, J., (2008). Environmental Water Requirements of the Gellibrand Estuary: Final Estuary FLOWS Report. Lloyd Environmental Pty Ltd Report to Corangamite CMA, Colac, Victoria, Australia.
- Matsumoto, J., Powell, G., Brock, D., 1994. Freshwater inflow needs of an estuary computed by Texas estuarine MP model. *Journal of Water Resources Planning and Management* 120, 693-714.
- Mattson, RA (2002). A resource-based framework for establishing freshwater inflow requirements for the Suwannee River Estuary. *Estuaries* 25, 1333-1342.
- MDBC, Murray Darling Basin Commission, 2000. Ecological need and opportunities for improved hydrological management in River Murray Barrages Environmental Flows: An evaluation of environmental flow needs in the Lower Lakes and Coorong. In: A. Good, P. Tucker, M. Long (Editors), Report to the Murray – Darling Basin Commission, Canberra, pp. 58-85.
- MDBC, Murray Darling Basin Commission., 2008. Murray-Darling Basin Rivers Ecosystem Health Check, 2004-2007, Sustainable Rivers Audit Report 1. Murray-Darling Basin Commission, Canberra.

- Midgley DC, Pitman WV and Middleton BJ (1994) Surface water resources of South Africa 1990. Vols. I-VI. *Water Research Commission Reports* No. 298/1.1/94 to 198/6.1/94, Pretoria, South Africa.
- Montagna PA, Alber M., Doering P, Connor MS (2002). Freshwater inflow: Science, policy and management. *Estuaries* 25, 1243-1245.
- Naiman RJ, Bunn SE, McClain ME, Vorosmarty CJ, Zalewski M (2006). The Science of Flow-Ecology Relationships: Clarifying Key Terms and Concepts. 7 pp. [www.unesco.org/water/ihp/ecoecology/pdf/](http://www.unesco.org/water/ihp/ecoecology/pdf/)
- Nielsen P, Hanslow DJ (1991) Wave runup distributions on natural beaches. *Journal of Coastal Research* **7(4)**: 1139-1152
- Olden JD and Poff NL (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* 19: 101-121.
- Olsen SB, Padma TV, Richter BD (2006). Managing Freshwater Inflows to Estuaries: A Methods Guide. US Agency for International Development, USAID Coastal Resource Center at the University of Rhode Island and the Nature Conservancy. USAID, Washington DC, 52 pp. <http://www.nature.org/initiatives/freshwater/files/methodsguidev61.pdf>
- Orth, D.J., Maughan, O.E., 1982. Evaluation of the incremental methodology for recommending instream flows for fishes. *Transactions, American Fisheries Society* 111, 413-445.
- Peirson, W.L., Bishop, K., Van Senden, D., Horton, P.R., Adamantidis, C.A., 2002. Environmental Water Requirements to maintain Estuarine Processes. Environmental Flows Initiative Technical Report Number 3. Commonwealth of Australia. Canberra. 158 pp. <http://www.environment.gov.au/water/publications/environmental/rivers/nrhp/estuaries.html>.
- Peirson, W.L., Nittim, R., Chadwick, M.J., Bishop, K.A., Horton, P.R., 2001. Assessment of changes to saltwater / freshwater habitat from reductions in flow to the Richmond River estuary, Australia. *Water Science and Technology* 43, 89-97.
- Perissinotto R, Blair A, Connell A, Demetriades NT, Forbes AT, Harrison TD, Iyer K, Joubert M, Kibridge I, Mundree S, Simpson H, Stretch D, Thomas C, Thwala X, Zietsman I (2004) Contributions to Information Requirements for the implementation of Resource Directed Measures for Estuaries *WRC Report 1247/2/04*
- Perissinotto R, Stretch DD, Taylor, R (eds) (2012). Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model. Cambridge University Press.
- Pitman, W. V. (1995). Towards improved utilisation of South Africa's water resources. Proceedings of the 7th South African National Hydrology Symposium, Grahamstown, September 1995. Rhodes University, Grahamstown, South Africa.
- Poff, NL, Richter, B, Arthington, AH, Bunn, SE, Naiman, RJ, Kendy, E, Acreman, M, Apse, C, Bledsoe, BP, Freeman, M, Henriksen, J, Jacobson, RB, Kennen, J, Merritt, DM, O'Keefe, J, Olden, J, Rogers, K, Tharme, RE, Warner, A, (2010). The Ecological Limits of Hydrologic Alteration (ELOHA): A new framework for developing regional environmental flow standards. *FRESHWATER*

- Powell GL and Matsumoto J (1994). Texas Estuarine Mathematical Programming Model: A tool for freshwater inflow management. In: K.R. Dyer, R.J. Orth (Editors), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Olsen and Olsen, Fredensborg, Denmark, pp. 401-406.
- Powell, GL, Matsumoto, J., Brock, D.A., (2002). Methods for determining minimum freshwater inflow needs of Texas Bays and Estuaries. *Estuaries* 25, 1262-1274.
- Prandle D (2009). *Estuaries. Dynamics, mixing, sedimentation and morphology*. Cambridge University Press, New York.
- Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10, 163-1174.
- Robins, J.B., Halliday, I.A., Staunton-Smith, J., Mayer, D.G., Sellin, M.J., (2005). Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and the application of a suggested approach. *Marine and Freshwater Research* 56, 343-360.
- Schofield, N., Burt, A., (2003). Issues in environmental water allocation – an Australian perspective. *Water Science and Technology* 48, 83-88.
- Schofield, N., Burt, A., Connell, D., 2003. Environmental water allocation, principles, practices, policies, progress and prospects. Canberra, Australia. Canberra Publishing and Printing. Land and Water Australia.
- Schulze, R.E. and Maharaj, M. 2007. A-Pan Equivalent Reference Potential Evaporation. In: Schulze, R.E. (Ed). 2007. **South African Atlas of Climatology and Agrohydrology**. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 13.2.
- Sherwood, JE (1983). *Hydrodynamics of the Gellibrand River Estuary*. Faculty of Applied Science and Technology, WIAE. Research Report 83-1. Prepared for the Rural Water Commission, Victoria. 102 pp.
- Sherwood, J.E., (1985). *Hydrodynamics of South West Victorian Estuaries*. Faculty of Applied Science and Technology, WIAE, Research Report 85-1. 27 pp.
- Slinger JH and Taljaard S (1990). Preliminary investigation of seasonality in the Great Berg Estuary. *Water SA* 20 (4), 279-287.
- Slinger JH, Taljaard S, Largier JL (1990). Changes in estuarine water quality in response to a freshwater flow event. In: Dyer, K.R., Orth, R.J. (Eds.), *Changes in Fluxes in Estuaries*. Olsen and Olsen, Denmark, pp. 51-54. ECSA22/ERF Symposium. International Symposium Series.
- Smakhtin VU (2001). Low flow hydrology: a review. *Journal of Hydrology* 240 (2001) 147-186
- Sun, T., Yang, Z.F., 2004. Calculating methods for ecological flows in estuary and its application in Haihe River basin. *Environmental Informatics Archives* 2, 464-470.

Swart DH (1974) Offshore transport and equilibrium beach profiles. *Delft Hydraulics Laboratory Pub.* **131**

Taljaard S, Snow G ; Gama P; Van Niekerk L (2009). Verification of a conceptual model of water quality for small temporarily open/closed estuaries: East Kleinemonde Estuary, South Africa. *Marine and freshwater research*. Vol. 60, No 3, pp. 234-245.

Taljaard S, Snow GC, Gama P, and van Niekerk L (2009). Verification of a conceptual model of water quality for small temporarily open/closed estuaries: East Kleinemonde Estuary, South Africa. *Marine and Freshwater Research* 60, 234-245.

Taljaard S, Van Niekerk L, Huizinga P and Joubert W (2003) Resource monitoring procedures for estuaries for application in the Ecological Reserve determination and implementation process. *Water Research Commission Report No. 1308/1/03*. Pretoria.

Taljaard S, van Niekerk, L and Joubert, W (2009). Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: Southern hemisphere perspective. *Estuarine, Coastal and Shelf Science*, Volume 85, Issue 3, 30 November 2009, Pages 407-421.

Taljaard, S., Adams, J.B., Turpie, J.K., Van Niekerk, L., Bate, G.C., Cyrus, D., Huizinga, P., Lamberth, S., Weston B., 2003. Methodology for the Determination of the Preliminary Ecological Reserve for Estuaries. Version 2. Department of Water Affairs & Forestry, Pretoria, South Africa.

Theron AK and Bergman S (2007). Relationships between estuarine and coastal parameters to predict/assess closed mouth state in SA estuaries. Oral Presentation & Book of Abstracts; *Fifth WIOMSA Scientific Symposium*, Durban 22-26 October, 2007; p 115.

Theron AK, Diedericks GPJ, Huizinga P, Basson GR and Kemp A (2002). Measurement and modelling of sediment dynamics in estuaries. In: *ENVIRO FLOWS*. 2002. Proceedings of the International Conference on Environmental Flows for River Systems, incorporating the 4th International Ecohydraulics Symposium. Cape Town, South Africa. March 2002.

Turpie JK, Adams JB, Joubert A, Harrison TD, Colloty BM, Maree RC, Whitfield AK, Wooldridge TH, Lamberth SJ, Taljaard S, and van Niekerk L (2002). Assessment of the conservation priority status of South African estuaries for use in management and water allocation. *Water SA*. 28, 2: 191-206.

Turpie, JK (2004) Improving the biodiversity importance rating of South African estuaries. *Water Research Commission*.

Turpie, JK and Clark, B (2007). The health status, conservation importance and economic value of Temperate South African estuaries and development of a regional conservation plan. C.A.P.E. Regional Estuarine Management Programme.

Turpie, JK, Adams, JB, Colloty, B, Joubert, A, Harrison, T, Maree, W, Taljaard, S, Van Niekerk, L, Whitfield, A, Wooldridge, T, Lamberth, S, Taylor, R, Weston, B and Mackay H (2000) Classification and prioritisation of South African estuaries on the basis of health and conservation status for determination of the estuarine water reserve. A report submitted to the Department of Water Affairs and Forestry: Social and Ecological Services. Pretoria.

- Van Ballegooyen, R, Taljaard, S, van Niekerk, L and Huizinga, P (2004). Using 3D modelling to predict physico-chemical responses to variation in river inflow in smaller, stratified estuaries typical of South Africa. *Journal of Hydraulic Research* Vol. 42, No. 6, pp. 563-577.
- Van Niekerk L, Bate GC & Whitfield AK (eds) (2008). An Intermediate Ecological Reserve determination study of the East Kleinemonde Estuary. Water Research Commission Report 1581/2/08, Pretoria
- Van Niekerk L, Huizinga P and Theron A. (2002). *Semi-closed mouth states in estuaries along the South African coastline*. In: Environmental Flows For River Systems Proceedings. Fourth International Ecohydraulics Symposium. Vol. 31 No. 1 (ISSN 0378-4738).
- Whitfield AK (1998) Biology and ecology of fishes in southern African estuaries. *Ichthyological monographs of the J.L.B Smith Institute of Ichthyology* 2: 223pp.
- Whitfield AK, Adams JB, Bate GC, Bezuidenhout K, Bornman TG, Cowley PD, Froneman PW, Gama PT, James NC, Mackenzie B, Riddin T, Snow GC, Strydom NA, Taljaard S, Terörde AI, Theron AK, Turpie JK, van Niekerk L, Vorwerk PD and Wooldridge TH (2008). A multidisciplinary study of a small, temporarily open/closed South African estuary, with particular emphasis on the influence of mouth state on the ecology of the system. *African Journal of Marine Science* 2008, 30(3): 453-473.
- Whitfield, A.K., Wooldridge, T.H., 1994. Changes in freshwater supplies to southern African estuaries: Some theoretical and practical considerations, In: K.R. Dyer, R.J. Orth (Editors), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Olsen and Olsen, Fredensborg, Denmark, pp. 41-50.

# APPENDIX A

## POLICIES, ACTS AND GUIDELINES APPLICABLE TO SA ESTUARIES

## 13. POLICIES, ACTS AND GUIDELINES APPLICABLE TO SA ESTUARIES

To clarify the roles and responsibilities of the various actors involved in managing activities in and around estuaries, Section 2 provides a brief summary of the legislation relevant to South Africa's estuaries. It is important to note that while an EWR study is conducted according to the guidelines promulgated under the National Water Act (Act 36 of 1998) (NWA) all proposed projects has to comply with a body of environmental and planning legislation. An overview of the relevant laws and regulations is provided in this section.

### 13.1 NATIONAL LEGISLATION

National legislation that is relevant to the development of in around the Bot River Estuary include:

- National Environmental Management Act (Act 107 of 1998);
- Marine Living Resources Act (Act 18 of 1998);
- National Environmental Management: Integrated Coastal Management (Act 24 of 2008);
- National Water Act (Act 36 of 1998);
- National Environmental Management: Biodiversity Act (Act 10 of 2004);
- National Heritage Resources Act (Act 25 of 1999);
- Local Government: Municipal Systems Act (Act 32 of 2000);
- Conservation of Agricultural Resources Act (No. 43 of 1983); and
- National Health Act (No. 61 of 2004).

A short summary on each of these are provided below.

#### 13.1.1 NATIONAL ENVIRONMENTAL MANAGEMENT ACT (ACT 107 OF 1998) (NEMA)

DEA is the lead agent for NEMA. NEMA ([www.info.gov.za/documents/acts/1998.htm](http://www.info.gov.za/documents/acts/1998.htm)) provides for co-operative environmental governance through the establishment of national environmental management principles, and procedures for their incorporation into decisions affecting the environment. NEMA emphasizes co-operative governance and assists in ensuring that the environmental right and related rights in the Constitution are protected. NEMA requires the Department of Environmental Affairs to be the lead agent in ensuring the effective custodianship of the environment.

In particular the Act provides that sensitive, vulnerable, highly dynamic or stressed ecosystems, such as estuaries require specific attention in management and planning procedures, especially where subjected to significant human resource usage and development.

Various of the activities listed in the NEMA Environmental Impact Assessment ("EIA") Regulations (which came into effect on 3 July 2006) bear on activities within the coastal zone and which require environmental authorisation before they can proceed. The EIA Regulations regulate procedures and

criteria for the submission, perusal, consideration and decision of applications for the environmental authorisation of specified activities. These regulations are especially pertinent to estuaries as many estuaries are situated within rapidly expanding development nodes along the South African coast and are under tremendous pressure from human activities. Waste disposal activities are also scheduled activities under these regulations.

### 13.1.2 MARINE LIVING RESOURCES ACT (ACT 18 OF 1998) AMENDED 2000 (MLRA)

The Department of Agriculture, Forestry and Fisheries is currently the lead agent for the MLRA. The objectives and principles of the MLRA deal with the utilization, conservation and management of marine living resources (including estuarine resources), the need to protect whole ecosystems, preserve marine biodiversity and minimize marine pollution, as well as to comply with international law and agreements and to restructure the fishing industry ([www.info.gov.za/documents/acts/1998.htm](http://www.info.gov.za/documents/acts/1998.htm)). Marine living resources includes any aquatic plant or animal, whether piscine or not, and any mollusc, crustacean, coral, sponge, holothurian or other echinoderm, reptile and marine mammals and includes their eggs, larvae and all juvenile stages, but does not include sea birds and seals.

Chapter 4 of the MLRA deals with the declaration of Marine Protected Areas and which empowers the Minister (DEA) to declare an area to be a Marine Protected Area where various activities are prohibited. These are stipulated in the Declaration of Areas as Marine Protected Areas (No R.1429, 29 December 2000) promulgated under the Act ([www.info.gov.za/documents/regulations/2000.htm](http://www.info.gov.za/documents/regulations/2000.htm)). The Bot River Estuary is included in the core set of estuaries that needs to be protected to meet biodiversity targets in South Africa (See section 4.1 for more detail).

### 13.1.3 NATIONAL ENVIRONMENTAL MANAGEMENT: INTEGRATED COASTAL MANAGEMENT ACT (ACT 24 OF 2008)

DEA: Chief Directorate: Oceans and Coast is the lead agent for the Coastal Management Act. In relation to the establishment of resource objectives, the Coastal Management Act ([www.mcm-deat.gov.za/regulatory/czb.html](http://www.mcm-deat.gov.za/regulatory/czb.html)) aims at establishing a system of integrated coastal and estuarine management in South Africa, including norms, standards and policies, in order to promote the conservation of the coastal environment, and the ecologically sustainable development of the coastal zone, to define rights and duties in relation to coastal areas, to determine responsible organs of state in relation to coastal areas and to give effect to South Africa's international obligations in relation to coastal matters and to provide for related matters.

Chapter 8 of the Coastal Management Bill contains exclusive provisions dealing with Marine and Coastal Pollution Control, specifically addressing 'Discharge of Effluent into coastal waters' (administered in collaboration with DWA) and 'Incineration and Dumping at sea' (e.g. dredge spoil dumping).

### 13.1.4 NATIONAL WATER ACT (ACT 36 OF 1998) (NWA)

DWA is the lead agent for the National Water Act. One the important objectives of the NWA is to ensure protection of the aquatic ecosystems of such South Africa's water resources ([www.info.gov.za/documents/acts/1998.htm](http://www.info.gov.za/documents/acts/1998.htm)). To be able to do this effectively, the NWA requires policies to be in place that provide guidance in developing resource quality objectives, i.e. specifying

aspects such as freshwater inflow, water quality, habitat integrity, biotic composition and functioning requirements.

Estuaries are classified as a water resource under NWA. Chapter 3, Part 3 of the NWA requires Classification and Resource Quality Objectives to be determined for all water resources, including estuaries. The Water Resource Protection Policy (under this Act) provides detailed guidelines and procedures for the classification (i.e. predefined health status) and the setting of Resource Quality Objectives for the protection of aquatic ecosystems (including objectives for water quantity, water quality, habitat integrity and biotic integrity). Section 21 of the NWA classifies a number of activities related to water supply/demand and waste disposal (from land-based activities) as 'water uses' that requires authorisation (licensing) by DWA. The Act also identifies certain land use (e.g. activities resulting in stream-flow reduction such as afforestation and cultivation of crops) and infrastructural developments (e.g. altering the bed, banks, course or characteristics of a watercourse) as 'water uses' that require authorisation by DWA.

### 13.1.5 NATIONAL ENVIRONMENTAL MANAGEMENT: BIODIVERSITY ACT (ACT 10 OF 2004)

DEA is the lead agent for the Biodiversity Act. The objective of the Biodiversity Act is to provide for the conservation of biological diversity, regulate the sustainable use of biological resources and to ensure a fair and equitable sharing of the benefits arising from the use of genetic resources ([www.info.gov.za/documents/acts/2004.htm](http://www.info.gov.za/documents/acts/2004.htm)). The Act states that the state is the custodian of South Africa's biological diversity and is committed to respect, protect, promote and fulfill the constitutional rights of its citizens. It also recognizes that South Africa is party to, amongst others, the Convention on Biological Diversity, the Convention on Wetlands of International Importance especially Waterfowl Habitat (Ramsar Convention) and the Convention on Migratory Species (Bonn Convention). The Bot River Estuary is included in the core set of estuaries that needs to be protected to meet biodiversity targets in South Africa (See Section 4.1 for more detail).

### 13.1.6 LOCAL GOVERNMENT: MUNICIPAL SYSTEMS ACT (ACT 32 OF 2000)

Department of Provincial and Local Government is the lead agent for the Municipal Systems Act. The Municipal Systems Act (Chapter 5) deals with Integrated Development Planning (IDPs) (municipalities are obliged to prepare and to update IDPs regularly) ([www.info.gov.za/documents/acts/2000.htm](http://www.info.gov.za/documents/acts/2000.htm)). An IDP is intended to encompass and harmonise planning over a range of sectors such as water, transport, land use and environmental management. It requires each local authority to adopt a single, inclusive plan for the development of the municipality.

Chapter 5 of the Municipal Systems Act deals with integrated development planning (IDP) that sets the social and economic objectives for a particular area. The Municipal Planning and Performance Management Regulations (Government Notice R.796, 24 August 2001) ([www.info.gov.za/documents/regulations/2001.htm](http://www.info.gov.za/documents/regulations/2001.htm)) promulgated in terms of this Act describe the content requirements of IDPs. The regulations, for example state that the Spatial Development Framework, reflected in the municipality's IDP, must 'contain a strategic assessment of the environmental impact of the spatial development framework'.

### 13.1.7 CONSERVATION OF AGRICULTURAL RESOURCES ACT (NO. 43 OF 1983) (CARA)

Department of Agriculture, Forestry and Fisheries is the lead agent for CARA. The objectives of CARA is to provide for the conservation of the natural agricultural resources of South Africa by: the maintenance of the production potential of land; the combating and prevention of erosion and weakening or destruction of the water sources (including estuaries); and the protection of the vegetation and the combating of weeds and invader plants.

### 13.1.8 NATIONAL HEALTH ACT (NO. 61 OF 2004) (NHA)

While the Department of Health is the lead agent, the implementation of this act is delegated to the local municipal and provincial authorities. The responsibility for rendering environmental health services under the NHA has been delegated to metropolitan and district councils as from 1 July 2004. Every metropolitan and district municipality must ensure that appropriate municipal health services are effectively and equitably provided in their respective areas. These include (insofar as it influences human health, except in ports): water quality monitoring; waste management; and environmental pollution control.

## 13.2 IMPORTANT REGULATIONS AND GUIDELINES

### 13.2.1 EFFECTIVE MANAGEMENT AND CONTROL OF COASTAL INFRASTRUCTURE DEVELOPMENT

Regulations and best practice guidelines to facilitate effective management and control of coastal infrastructure development are listed below:

Responsible department	Regulation/ guideline
DEA	<p><u>NEMA EIA Regulations (2006)</u> (<a href="http://www.info.gov.za/documents/regulations/2006.htm">www.info.gov.za/documents/regulations/2006.htm</a>). The NEMA EIA Regulations commenced with effect from 3 July 2006 and require that the potential impacts on the environment, socio-economic conditions and cultural heritage must be investigated and assessed prior to implementation and reported to the authority charged with authorizing, permitting or otherwise allowing the implementation of an activity as listed in the NEMA EIA Regulations (2006). Activities that require a Basic Assessment, as well as the competent authorities responsible for administering these applications, are listed in Government Notice No. R386 and include activities such as dredging, excavation, infilling and removal of soil. Government Notice No. R387 lists activities that require Scoping and Environmental Assessment (i.e. a 'full EIA') and include, for example, development activities which exceed 20 hectares or more; and construction or earth-moving activities in the sea or within 100 metres inland of the high-water mark of the sea.</p>
SABS	<p>Building Regulations and Standards. The NBRs set standards for the technical performance for all buildings constructed in South Africa, mainly to ensure the health and safety of occupants. These are available from the SABS (<a href="https://www.sabs.co.za/Business_Units/Regulatory/RegulatedProducts_Services/Architecture/Overview.aspx">https://www.sabs.co.za/Business_Units/Regulatory/RegulatedProducts_Services/Architecture/Overview.aspx</a>).</p>

Responsible department	Regulation/ guideline
DEA	<p><u>A Policy for Coastal Zone Management in the Republic of South Africa. Part 2: Guidelines for coastal land-use (published by the Council for the Environment August 1999 under the then National Conservation Act (No 73 of 1989):</u> The document provides best practice guidelines for land-use and the protection of coastal landforms such as rivers, floodplains, estuaries wetlands and coastal lakes, Dunes, Beaches, Cliffs and steep slopes, Rocky shores, marine sub-tidal zones and coastal islands.</p>
DEA	<p><u>Regulations on Sensitive Areas</u> (promulgated under Environmental Conservation Act (No. 73 of 1989) and remain in force until replaced with the new regulations under NEMA.</p>
DEA	<p>Guidelines for the Control and Management of Activities in Sensitive Coastal Areas, include (<a href="http://sacoast.uwc.ac.za/publications/">http://sacoast.uwc.ac.za/publications/</a>):</p>
DEA	<p><u>NEMA EIA Guidelines.</u> In order to assist potential applicants, environmental assessment practitioners, and interested and affected parties to understand what is required of them in terms of the NEMA EIA Regulations (2006), what their rights are and/or what their roles may be, DEAT is in the process of preparing a series of national guideline documents. A series of Integrated Environmental Management (IEM) information documents (not guidelines) is also available: <a href="http://www.environment.gov.za/services/documents/publications/eia_info_series_24062003.html">www.environment.gov.za/services/documents/publications/eia_info_series_24062003.html</a>.</p>
DEADP (Western Cape)	<p>A series of guidelines related to environmental assessment and management (2005). The purpose of these guidelines is to improve the efficiency, effectiveness and quality of environmental assessment and management processes in the Western Cape Province. (<a href="http://www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/G">www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/G</a>).</p> <p><u>Draft guidelines in terms of requirements of the NEMA EIA Regulations (2006).</u> (<a href="http://www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/D">www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/D</a>):</p>
DEADP (Western Cape)	<p><u>Guidelines for Resort Developments (2005)</u> (<a href="http://www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/G">www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/G</a>). These guidelines address resort developments in the rural areas of the Western Cape, outside the edges of urban areas and within sensitive areas on the urban fringes</p>
DEADP (Western Cape)	<p><u>A Manual for the Application of Bioregional Planning in the Western Cape Province</u> (<a href="http://www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/M">www.capecapegateway.gov.za/eng/your_gov/3576/pubs/guides/M</a>), sets out planning guidelines for local and provincial government for the preparation of Integrated Development Plans, Spatial Development Frameworks and Spatial Development Plans in order to contribute to the creation of a safer environment and to protect, enhance and promote the total environment for the optimal development of the people.</p>
DWA	<p><u>Water Use Authorisation Process for Individual Applications</u> (<a href="http://www.dwaf.gov.za/Documents/">www.dwaf.gov.za/Documents/</a>). To assist applicants in the authorisation process under Section 21 of the NWA, DWA has compiled a manual describing the administrative procedures and parties to be involved at different stages of the authorisation process.</p>

Responsible department	Regulation/ guideline
DWA	<u>Regulations for recreational use of water resources</u> ( <a href="http://www.dwaf.gov.za/Documents/Other/RMP/rwum.asp">www.dwaf.gov.za/Documents/Other/RMP/rwum.asp</a> ). DWAF is in the process of drafting these regulations which will also apply to estuaries

### 13.2.2 WASTEWATER DISCHARGES TO THE MARINE (INCLUDING ESTUARIES) ENVIRONMENT

Regulations and best practice guidelines that wastewater discharges to the marine (including estuaries) environment are listed below:

Responsible department	Regulation/ guideline
DEA	<u>NEMA EIA Regulations (2006)</u> ( <a href="http://www.info.gov.za/documents/regulations/2006.htm">www.info.gov.za/documents/regulations/2006.htm</a> ). The NEMA EIA Regulations commenced with effect from 3 July 2006 and require that the potential impacts on the environment, socio-economic conditions and cultural heritage must be investigated and assessed prior to implementation and reported to the authority charged with authorizing, permitting or otherwise allowing the implementation of an activity as listed in the NEMA EIA Regulations (2006).
DWA	<u>General Authorisations (2004)</u> ( <a href="http://www.info.gov.za/gazette/notices/2004/26187a.pdf">www.info.gov.za/gazette/notices/2004/26187a.pdf</a> ) These are promulgated in terms of section 39 of the NWA (1998). The authorisation permitted in terms of this Schedule replaces the need for a water user to apply for a licence in terms of the NWA (1998) for a water use provided that the use is within the conditions set out.
DWA	<u>Water Use Authorisation Process for Individual Applications (DWAF, 2000)</u> ( <a href="http://www.dwaf.gov.za/documents.asp">www.dwaf.gov.za/documents.asp</a> ): A manual to assist applicants in the authorisation process under Section 21 of the NWA (1998) and which describes the administrative procedures and parties to be involved at different stages of the authorisation process.
DWA	<u>Strategy for a Waste Discharge Charge System, 2003</u> ( <a href="http://www.dwaf.gov.za/documents.asp">www.dwaf.gov.za/documents.asp</a> ). The Department is in the process of developing this strategy for land-derived wastewater aimed at: a) promoting the sustainable development and efficient use of water resources, b) promoting the internalisation of environmental costs by impactors; and c) recovering some of the costs of managing water quality (i.e. some form of an incentive system).
DWA, to be transferred to DEA	<u>Operational Policy for the Disposal of Water containing Waste to the Marine Environment of South Africa (DWAF, 2004e)</u> ( <a href="http://www.dwaf.gov.za/documents.asp">www.dwaf.gov.za/documents.asp</a> ). This policy needs to be reviewed and updated – see recommended actions.

Note, since 1985 the design of discharges to the marine environment has followed the **receiving water quality objectives approach where effluent quantities and composition must be within limits that would meet site-specific Environmental Quality Objectives**, as recommended in the South African Water Quality Guidelines for Coastal Marine Waters (DWAF, 1995). This approach is largely in

agreement with the requirements of the *Operational Policy for the Disposal of Water containing Waste to the Marine Environment of South Africa* (DWAF, 2004). Of great concern in South Africa is the rapid increase in discharges to less physically dynamic and more ecologically sensitive areas such as the *surf zone* and *estuaries*, where effluents and diffuse sources are adversely affecting the marine environment, albeit in a localized manner. However, the operational policy for the disposal of land-derived wastewater (DWAF, 2004) should, in future, also require improved management and control of these estuarine and surf zone discharges.

# APPENDIX C

## DETAILED CASE STUDY: BREEDE ESTUARY EWR

### Background and over view of estuaries EWR method

The National Water Act (Act 36 of 1998) in South Africa only recognizes two water rights: basic human needs reserve ( $25 \text{ l person}^{-1} \cdot \text{d}^{-1}$ ) and the freshwater reserve (the ecological water requirement) to sustain aquatic ecosystems in a healthy condition. The act provides for a reserve to be determined prior to the authorization of water use (e.g. for agriculture, large volume residential and industrial uses) through licensing. This required South African estuarine scientists, in collaboration with the Department of Water Affairs and Forestry (DWAF), to develop a method to determine the ecological water requirements of estuaries (DWAF, 2004; Adams et al., 2002).

The method includes delineating the geographical boundaries of the estuary and determining estuarine health by comparing the present state of the estuary with a predicted reference condition using an Estuarine Health Index (DWAF, 2004; Turpie, 2002). The Estuarine Health Index comprise an evaluation of the habitat health (abiotic variables: hydrology, hydrodynamics, mouth status, water quality, physical habitat alteration) and biological health (biotic variables: microalgae, macrophytes, invertebrates, fish, and birds). Both abiotic and biotic variables are evaluated as the relationships between the variables are often not well understood and the biotic response to certain abiotic variables can be slow (Turpie, 2002). The accuracy with which the health of any estuary can be described depends on the availability of historical data, additional data collected within time and budget constraints, and the complexity of a particular estuary (Adams et al., 2002). The description of the present state and reference condition can therefore vary from a detailed quantitative evaluation based on measured data, to a narrative statement based on expert opinion. For this reason the confidence level (high, medium, or low) of each assessment is also documented. For South African estuaries the reference condition usually refers to its ecological status about 100 years ago before catchments were altered or the large scale manipulation of estuary mouths occurs. Under the reference condition an estuary refers receives 100% of the natural mean annual runoff (MAR) from the catchment, which is derived from modelled hydrology.

The importance of the estuary as an ecosystem is taken from a national rating system and together with the present health is used to set the future desired condition (an Ecological Reserve Category) for the estuary (Turpie et al., 2002; Turpie, 2004). Freshwater is then reserved to maintain the estuary in the defined condition.

The estuary reserve (the quantity and quality of freshwater required for the estuary) is determined through assessing a number of realistic monthly river flow scenarios, together with data (measured or modeled) for the present state (and reference conditions where available), to evaluate the extent to which abiotic and biotic conditions within an estuary are likely to vary with changes in river inflow. Results from these evaluations are used to select an acceptable river flow scenario that represents the highest reduction in freshwater inflow that will still maintain the estuary in the desired condition.

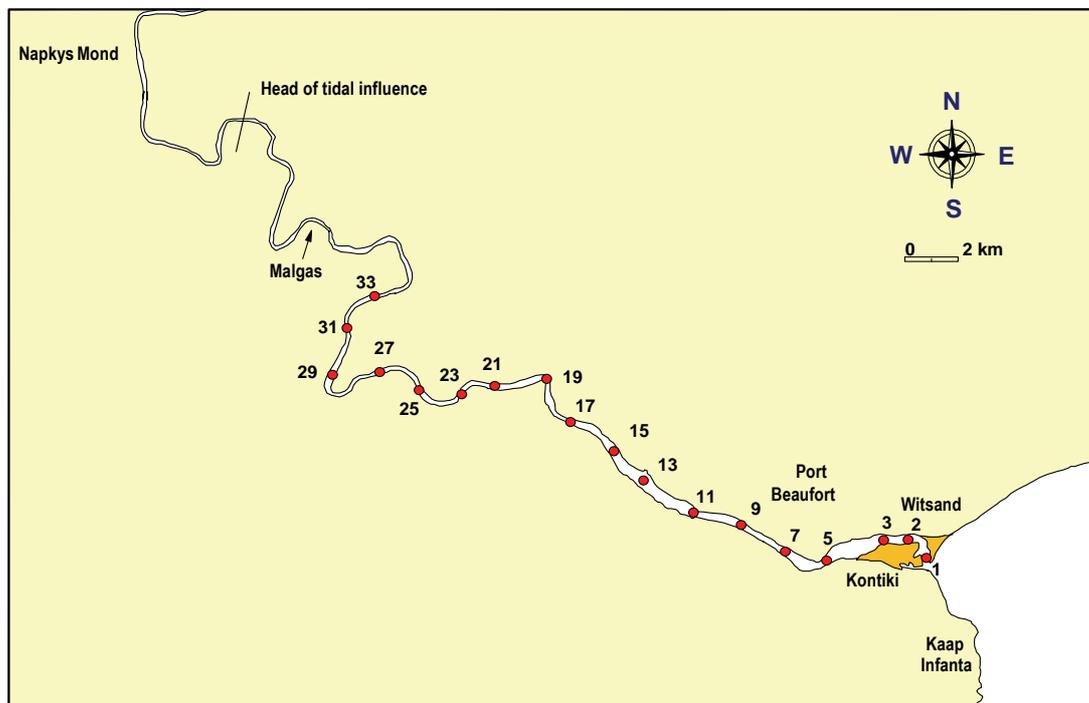
This section describes the application of the Reserve methodology on an Intermediate level to the Breede Estuary, focussing on the hydrodynamic component. The hydrodynamics component is the prediction platform from which all other predictions stem, e.g. water quality, estuarine macrophytes or fish.

An Intermediate level reserve study specifies that the overall confidence in the study results must be at a medium level (between a 40 to 80% surety in the predictions). At the same time, the method constrains the investigation to only two field data collection trips, focussing on the high and low flow

period respectively. As estuarine ecosystems are highly dynamic, such limited data collection can curtail the development of the necessary scientific insight into the system dynamics for sound predictive capabilities. The constraint in the data collection (normally imposed financially) can therefore result in a lower confidence in the results than required by the decision makers. The greater the proposed impact of a future development the higher the confidence in the prediction should be. For example, the development of large impoundments or transfer schemes poses a significant risk to the aquatic ecosystem and require large infrastructure investment, therefore the overall confidence in the prediction of the impacts of such developments (both ecological and socio-economic) should be high to medium.

### Case study area

The Breede River has a length of about 257 km with a catchment area of about 12 625 km<sup>2</sup>. Runoff from the catchment is strongly seasonal, with high flows and major floods during winter months (June to Augusts) and low flows during the summer (February to March). There are three major dams on the Breede River: the Riviersonderend Dam built in 1980, which has a capacity of 433 x 106 m<sup>3</sup>, the Brandvlei Dam built in 1926 with a capacity of 304 x 106 m<sup>3</sup> and the Kwaggaskloof Dam, built in 1975 with a capacity of 171x 106 m<sup>3</sup>. Additionally, there are several smaller dams in the catchment and many farm dams. The mean annual run-off (MAR) of the river reaching the estuary has as a result been reduced by approximately 42% from 1784 x 106 m<sup>3</sup> under reference (or natural) conditions to 1034 x 106 m<sup>3</sup> at present. The Breede Estuary is located in the warm temperate biogeographically zone of South Africa. The estuary stretches roughly from 10 km above Malagas to the town of Witsand some 220 km east of Cape Town (Figure B1).



**Figure B.1. The Breede River Estuary, showing the water column sampling stations**

The estuary enters the sea through a permanently open mouth located at the southern end of an extensive sand spit. The channel of the estuary is incised in the coastal plain and depths of 3 to 6 m

and even more are common over the first 28 km. Tidal influence extends beyond the pont at Malgas to approximately 50 km upstream. The Breede Estuary is generally well-mixed with some stratification observed during neap tides and periods of elevated flow. The mouth of the Breede Estuary is permanently open because of the high tidal flows and relatively high run-off of the system. It is considered highly unlikely that the mouth will close under present day conditions.

A consequence of catchment developments (current and future) was that changes in low flow conditions (a reduction in baseflow and longer duration of low flow periods) would result in increased salinity penetration upstream in the estuary. Seeing that the study team were only allowed to measure the systems response to change river inflow *in situ* twice, this short coming had to address through numerical modeling. As the Breede Estuary is a shallow, generally well mixed system, it lends itself very well to one dimensional (1D) modelling numerical modelling of the relatively simple hydrodynamic process of the Breede Estuary (van Ballegooyen *et al.*, 2004).

### **Numerical modeling of the Breede Estuaries sensitivity to flow**

The Mike 11 modelling system was applied to the estuary to simulate the effects of low flow conditions on the salinities. The modelling system, which was developed in the 1970s at the Danish Hydraulics Institute and regularly upgraded since then, has been applied locally and worldwide in various investigations (Yan, 1998; Refsgaard and Knudsen, 1996; Slinger et al., 1997; CSIR, 1993, 1998, 1999; DHI, 2001). It is an advanced and user-friendly 1D dynamic modelling system for rivers and estuaries. The hydrodynamic module is the basic module in Mike 11; additional modules can be used for simulations of transport dispersion, water quality and sediment transport. The hydrodynamic and transport dispersion modules were used in the investigations described in this paper. The Mike 11 system can be operated on a microcomputer for simulations periods of several months to years, dependent on the size of the model.

#### *Data availability, model setup and calibration*

The model was set up with bathymetric data collected at 1 km intervals. The bathymetric data used in this study was obtained from existing data sets (1982 and 1996) collected as part of a monitoring programme of estuaries undertaken by the CSIR for the Department of Environment Affairs and Tourism, South Africa (CSIR, 2000). The estuary is up to 1.25 km wide near the mouth and gradually becomes narrower further upstream with a width of 150 metres at Malgas, approximately 40 km upstream. The depths are mostly between three and six metres. A deep spot with a maximum depth of 17 metres below mean sea level (MSL) was observed at 19 km from the mouth. The data was deemed of an acceptable quality as there had been no significant changes as results of scouring or deposition in the estuary between 1996 and the modelling study.

The model was calibrated using recorded: river inflow data, water level data (5 stations) and salinity data (10-20 stations) collected along length of the estuaries over a neap and spring tide. Predicted water level variations in the ocean (Mossel Bay) were used as an open boundary in the marine environment.

#### *River inflow*

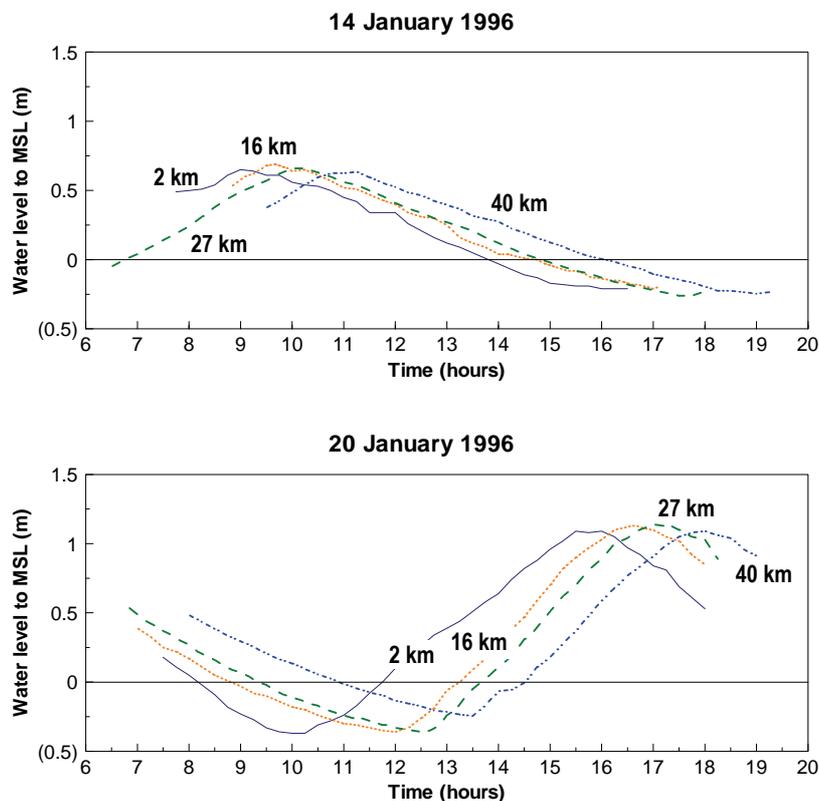
Two gauging stations are present in the lower part of the Breede River catchment, the Swellendam Station, H7H006-A01 (catchment size 9840 km<sup>2</sup>) on the main river, contributing the majority of the runoff and the Eenzaamheid Buffeljags Dam Station, H7H013-A01, (catchment size 602.00 km<sup>2</sup>) on the Buffeljags tributary which contributes to the runoff mainly during freshets and flood events. These gauging station are about 50 km above the head of the estuary and represent about 83% of the

catchment area. A delay of about a day was estimated before these measured flows could reach the estuary. The measured average daily flows for the two flow gauging stations were combined to estimate the total average daily inflow ( $\text{m}^3/\text{s}$ ) into the estuary.

Measured runoff data from October 1995 to September 1996 and October 2000 to September 2001 were used to calibrate the Mike 11 model. These periods coincide with the salinity data collection exercises, January 1996, February 2000, March 2000 and August 2000.

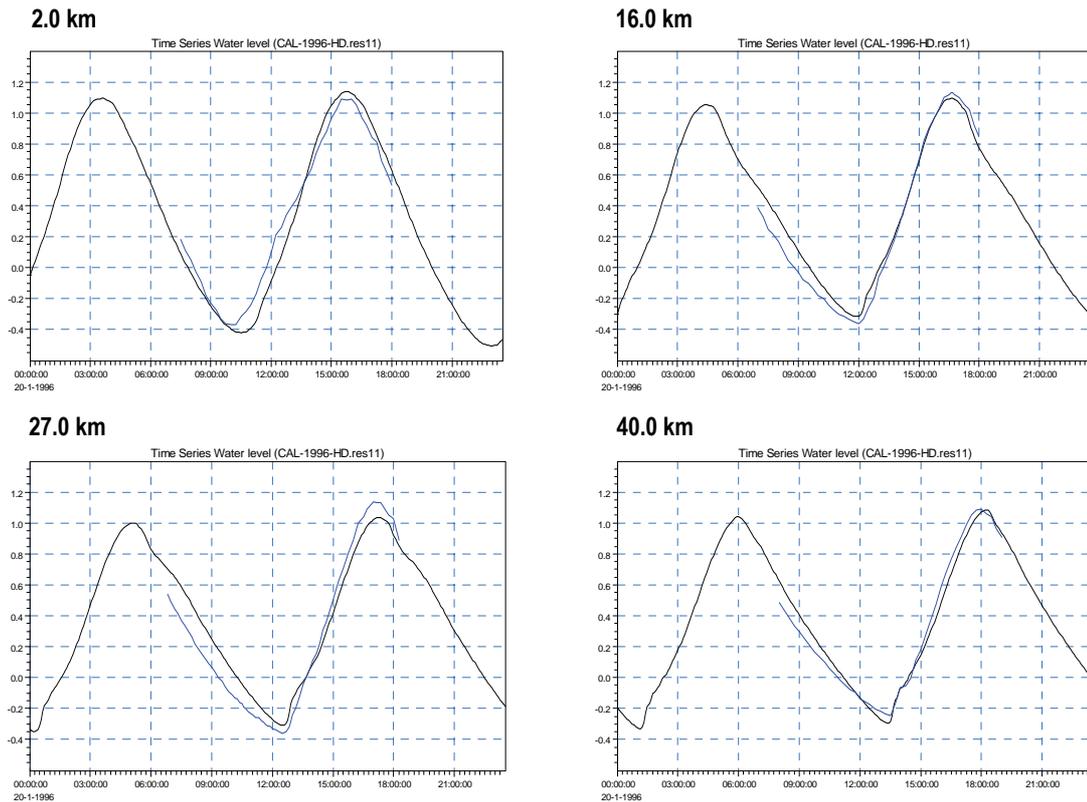
#### Water level data

Water level variations were measured by visual observations from gauging staff at four positions in the estuary at spring tide on 20 January 1996. Delays in the tidal flows of up to 4:00 hrs and 2:20 hrs were observed 39 km upstream on the low and high tide respectively. Water level variations were also observed at Napkys Mond, 58 km upstream, but tidal variation was not observed at this location. The water level data, collected on 14 and 20 January 1996 at 2.0 km, 16.0 km, 27.0 km and 40.0 km from the mouth (Figure B2) was used to calibrate the hydrodynamic module of the model.



**Figure B.2. Water levels data collected at 2.0 km, 16.0 km, 27.0 km and 40.0 km from the mouth at a neap tide (14 January 1996) and a spring tide (20 January 1996)**

The comparison of water level variations obtained from model simulations with the recorded water level variations for the spring tide, 20 January 1996, is shown in Figure B.3. In general, an acceptable agreement between measured and simulated water levels variations was obtained.



**Figure B.3. Comparison of water level variations obtained from model simulations with the recorded water level variations for the spring tide, 20 January 1996**

#### *Evaporation*

Evaporation was incorporated as an outflow from the model to account for evaporative losses and increases salinities. The evaporation (in mm) together with surface area of the estuary was used to estimate evaporation rate in  $\text{m}^3/\text{s}$ .

#### *Salinity*

Water quality measurements were collected from a series of stations in the Breede Estuary on January 1996 (summer), February 2000 (summer) and August 2000 (winter). In situ measurements of salinity and temperature profiles were taken at selected hydrographic stations (Figure B.1) along the length of the estuaries at approximately 0.5 m depth intervals. The advection and dispersion module of the model was calibrated using the measured river inflow data from December 1995 to January 1996 and salinity distributions measured on 20 January 1996. December 1995 was a high runoff month, with flows varying between  $17.4 \text{ m}^3/\text{s}$  and  $122.9 \text{ m}^3/\text{s}$ . At such high flows the estuary will be nearly completely fresh during a low tide and this condition with salinity concentrations being zero was therefore used as the starting condition for the estuary in the model. River flow recorded upstream in the Breede River during December 1995 and January 1996 was used for the upstream open boundary of the model. The best comparison of model results with measured salinity distribution data on 20 January 1996 was obtained at a dispersion coefficient of 60 used throughout the model and this dispersion coefficient was therefore used for further model simulations. In general, an acceptable agreement between measured and simulated data was obtained.

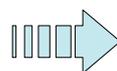
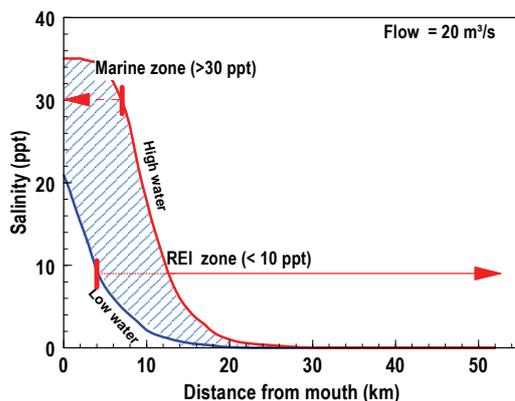
## Hydrodynamic States

Based on 1) the **salinity distributions** characteristic of the Breede Estuary as gleaned from the measured and modelled data, 2) **average flow distribution** under the reference and present flow scenarios and 3) the **habitat features** of the Breede Estuary five typical hydrodynamic states were identified. The occurrence and duration of these states varies depending on river inflow rate. These hydrodynamic states were described in terms of: typical flow patterns, flood plain inundation, tidal variations, salinity distributions, temperature, pH, suspended solids, dissolved oxygen and nutrients. For the purpose of this paper the discussion will only focus on the response of the salinity gradient to change in river inflow.

Previous studies on South African estuaries highlighted the importance of the River-Estuarine-Interface Zone (REI) as a highly productive area important to numerous estuarine related species. At the request of the biologist special attention was given to this area and the REI zone was upfront defined as the area in the estuary where salinities are <less than 10pp.

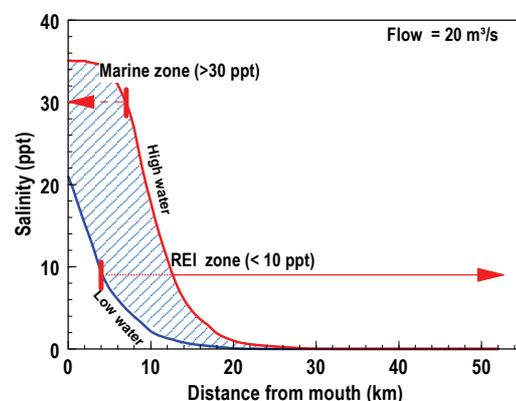
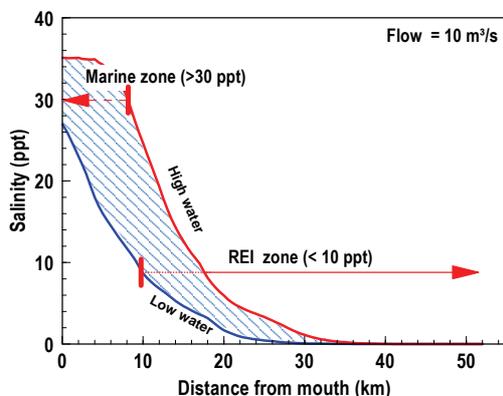
The five Abiotic States derived for the Breede River Estuary correlated with specific inflow ranges. For each flow range, two graphs are provided to illustrate the extent of saline penetration for the highest and lowest flow in the range. The graphs depict a spring high tide and spring low tide after a model simulation period of 4 months at a constant flow rate. Four months was the average duration of most hydrodynamics states.

### State 1: Strongly freshwater dominated at flows greater than $20 \text{ m}^3 \text{ s}^{-1}$

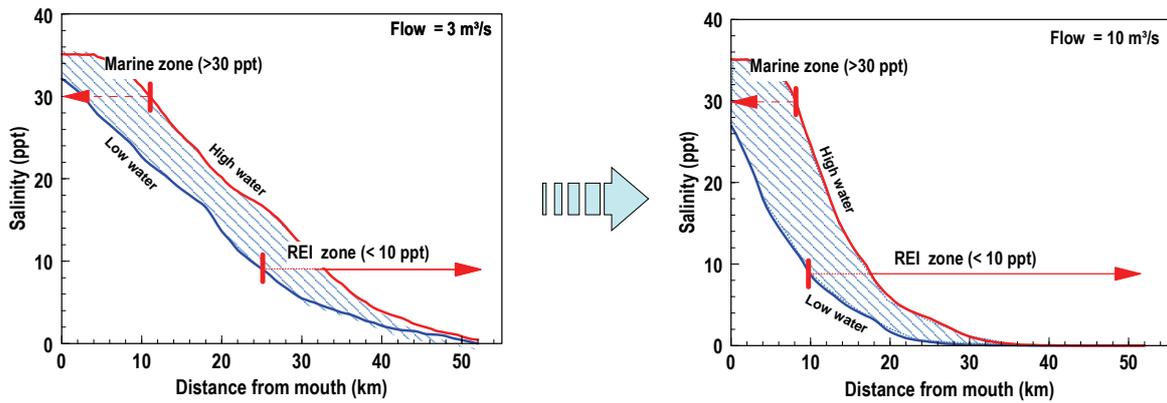


Completely fresh

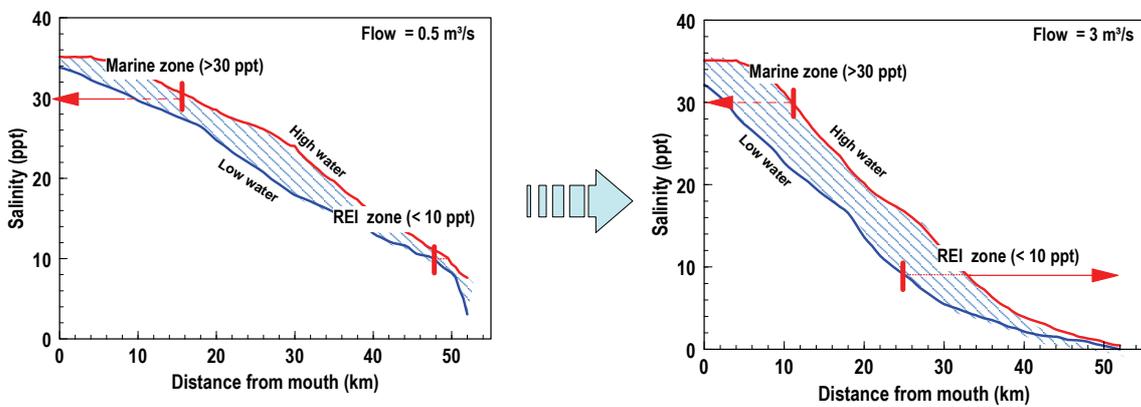
### State 2: Freshwater dominated with significant saline intrusion in lower reaches at flows between $10$ and $20 \text{ m}^3 \text{ s}^{-1}$



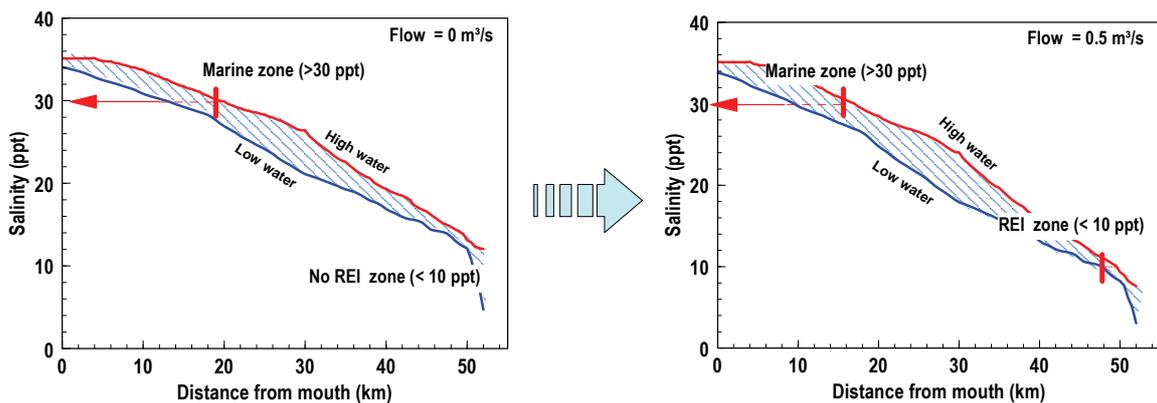
**State 3: Marine and freshwater influence on the estuary is balanced, with a well-developed REI zone at flows between  $3$  and  $10 \text{ m}^3 \cdot \text{s}^{-1}$**



**State 4: Marine dominated, where the REI zone is variable, depending on the flow rate and duration at flows between  $0,5$  and  $3 \text{ m}^3 \cdot \text{s}^{-1}$**



**State 5: Strongly marine dominated, with no REI zone at flows less than  $0.5 \text{ m}^3 \cdot \text{s}^{-1}$**



Hydrology and Changes in occurrence (the duration and frequency) of the abiotic states within Different Scenarios

Hydrological data (simulated mean monthly river flow scenarios) for reference conditions, present conditions and four future development scenarios covered a 64-year period (1927 to 1990). Standard South African hydrological models were used (Pitman, 1995; Midgley, Pitman and Middleton, 1994) to generate these simulated monthly flow scenarios to the estuary.

The simulated monthly runoff for the reference condition hind-casts the flow regime to the estuary before any catchment development occurred (Table B.1). The simulated monthly runoff scenario for the present state comprises all catchment development up to 2000. The Limited future development incorporated two winter flow diversions schemes (Michells Pass and Upper Molenaars). The moderate future development included an additional implementation of the Ouplaas diversion scheme and the raising of Buffeljags Dam impact. The high future development scenarios, Bromberg and Le Chasseur, both represent large instream dam developments which can potentially severely reduce the high and low inflows to the estuary.

**Table B.1: Summary of the simulated runoff to the Breede Estuary**

Scenario	Mean Annual Runoff ( $10^6 \text{ m}^3 \cdot \text{a}^{-1}$ )	% Reduction
Reference Condition	1785	
Present State	1034	42.1
Limited Future Development	954	46.6
Moderate Future Development	863	51.7
Bromberg Dam Future Development	772	56.7
Le Chasseur Dam Future Development	649	63.6

As South Africa is a semi-arid country and can show significant fluctuations in rainfall patterns between wet and dry periods, the runoff to the estuary need to be simulated for a long a period as possible (Davies and Day, 1998). Availability of reliable rainfall data and measured runoff data for calibration of the hydrological model(s) determines the period for which simulated mean monthly river runoff data can be provided to the estuary. Using long-term simulations provides a means of placing current estuarine measurements in the context of long-term variability, e.g. were the study conducted during a wet or dry period. For example, an analyse of the long-term present flows indicated that the mean monthly flows to the estuary were often below  $10 \text{ m}^3 \cdot \text{s}^{-1}$  in summer, while most of the *in situ* measurements correlated with flow above  $10 \text{ m}^3 \cdot \text{s}^{-1}$ . This meant that the study team never measured the full extent of salinity penetration in the system. In fact the sampling results were closer to the reference condition than to the present state or any of the future scenarios.

The hydrodynamic states, in turn, were superimposed on the monthly river flow scenarios to evaluate changes in occurrence (the duration and frequency) of the abiotic states under the simulated flow sequences. Of particular importance were changes in the occurrence and duration of the different hydrodynamic states in the median monthly flows and 10%ile flows, as they represent normal and drought periods, respectively.

**Table B.2. Comparison of the distribution and occurrence of abiotic states among the different runoff scenarios, representative of normal (median) flow conditions (states representing low flow periods, i.e. flows of  $< 10 \text{ m}^3 \cdot \text{s}^{-1}$  are shaded)**

SCENARIO	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Reference Condition	3	3	3	2	1	1	1	1	1	1	1	2
Present State	4	4	3	3	2	1	1	1	1	1	3	3
Limited Future Development	4	4	3	3	2	1	1	1	1	2	3	3
Moderate Future Development	4	4	4	3	3	2	1	1	1	2	3	3
Bromberg Future Development	4	4	4	3	3	2	1	1	1	2	3	4
Le Chasseur Future Development	4	4	4	3	4	3	2	1	1	2	3	3

A comparison of the occurrence of hydrodynamic states under median flow conditions under the different runoff scenarios is presented in Tables B.2. What becomes quite clear from the analysis is that State 1 and 2 (representing a freshwater rich system) used to be the dominating states under the reference condition in the Breede Estuary. These states have been significantly reduced under the present state, from occurring nine months under the reference conditions to six months under the present state. The Limited Future Development scenario showed a similar distribution to the present state, while the Moderate and Bromberg Future Development scenarios reduce the occurrence of the freshwater associated state to only 5 months of the year under median flow conditions. The Le Chasseur Future Development scenario represented the most severe reduction in freshwater inflow to the estuary as State 1 and 2 only occurred for 4 months under the median flow conditions.

The analyses not only shows the overall loss of freshwater inflow to the system, but it also highlights the fact that the extend of saline penetration has increase significantly from the reference condition. Under the median flow conditions under the reference conditions State 4 and 5 never occurred and the REI Zone ( $< 10\text{psu}$ ) started about 20 to 30 km upstream from the mouth. Both these states occur at present in the system, with the REI zone only starting to develop about 30 km to 45 km upstream from the mouth during the low flow period. Both the Moderate and Bromberg Future development scenarios showed an addition increase in the occurrence of state 4 and 5. Interesting enough, while the maximum development scenario, Le Chasseur, showed an increase in States 4 (now occurring for 5 months of year) under median flow conditions, it had a decrease in the occurrence of State 5, due to an increase in return flow from agricultural activities. In other word, while the duration of the low flow period increased the maximum salinity penetration remained the same as for Bromberg.

Results of the numerical modelling were also used to calculate average and maximum salinity penetration during the low flow period for the various scenarios based on the duration and area cover under different salinity regimes ( $< 10 \text{ psu}$ ,  $10\text{-}20 \text{ psu}$ ,  $20\text{-}30 \text{ psu}$ ,  $>30 \text{ psu}$ ). These results in turn provided the platform from which biotic changes could be hind-casted (reference conditions) or predicted (future scenarios). All changes were evaluated in relation to the reference condition. For example, under the reference conditions the REI zone ( $< 10 \text{ psu}$ ) occurred on average under low flows from about 19 km upstream from the mouth. Under the Present state and the Limited Development Scenarios it only starts as 28 km upstream (decreasing by 9 km) under average low flows. REI zone reduced by even more under the Moderate, Bromberg and Le Chassuer future scenarios, starting at 30, 34 and 32 km respectively.

Another key finding of the study was that the impact of droughts would be much more severe under the future scenarios. The modelling indicated that during an extreme drought situation under the reference conditions the REI zone started at 31 km upstream from the mouth and salinities of < 1 psu would still occur at the head of the system about 52 km from the mouth. Under the present state, limited and moderate future scenarios the REI zone would not occur in the estuary and maximum values of 14, 14 and 17 psu would occur at the top of the estuary respectively. Under the maximum development scenarios, Bromberg and Le Chasseur, the effect of droughts would be buffered by an increase in return flow from agriculture with the REI zone occurring at 47 km upstream from the mouth and values of 7 and 6 psu measured respectively.

An important habitat feature of the Breede Estuary is the start of the reed beds (*Phragmites australis*) about 12 km upstream from the mouth. Unless these reeds are rooted in ground water, they can only tolerate salinities > 20 psu for about three months before die-back start occurring (Adams and Bate, 1999). Numerical modelling was used to evaluate the duration of specific saline conditions at 12 km from the mouth. Under the reference conditions, the 20 psu zone never persisted for long under normal flows and only lasted about three months under drought conditions. This contrasted sharply with the Present and Limited future scenario under which salinity > 20 psu will be recorded for four to five months under normal flow condition and between six to eight months under drought conditions. The duration of the exposure of the start of the reed bed to high salinities would increase even more from five to seven months under the Moderate, Bromberg and Le Chasseur future scenarios causing permanent habitat modification and a ripple effect up the estuarine food chain.

#### **Effects of Prolonged Low Flows under Different Scenarios**

Additional consideration also had to be given to the specific habitat requirements of the species living in the system, e.g. the reeds beds starting to grow ~12 km upstream from the mouth cannot tolerate salinities > 20 psu for more than 3 months before they start dying back. During the low flow periods (months when flows are less than 10 m<sup>3</sup>/s) salinity distribution patterns in the estuary do not necessarily reach a steady state, but tend to progressively increase upstream until river flows increase towards the end of the low flow period. Figure B.5 illustrates the progressive saline intrusion that occurs during the low flow period for the different scenarios, using both the median flows (assumed to be representative of normal flow periods) and the 10%ile flows (assumed to be representative of drought periods) obtained from the 64-year simulated run-off datasets. The duration of the low flow period for each of the scenarios is indicated on the figures.

The results show a significant further upstream intrusion of salinity under present state compared to the reference conditions. This trend is also very pronounced under the range of future development scenarios. Although the low flow period under the drought conditions, in the Le Chasseur Scenario (12 months) last longer in comparison with the Moderate Development Scenario (10 months), the maximum salinity penetration in the former is less due to the elevated base flows, i.e. flows seldom fall within the 0.5 m<sup>3</sup>s<sup>-1</sup> range.

A summary of predicted salinity distribution patterns in the estuary during the low flow period, for the different scenarios, are presented in Tables B.6.

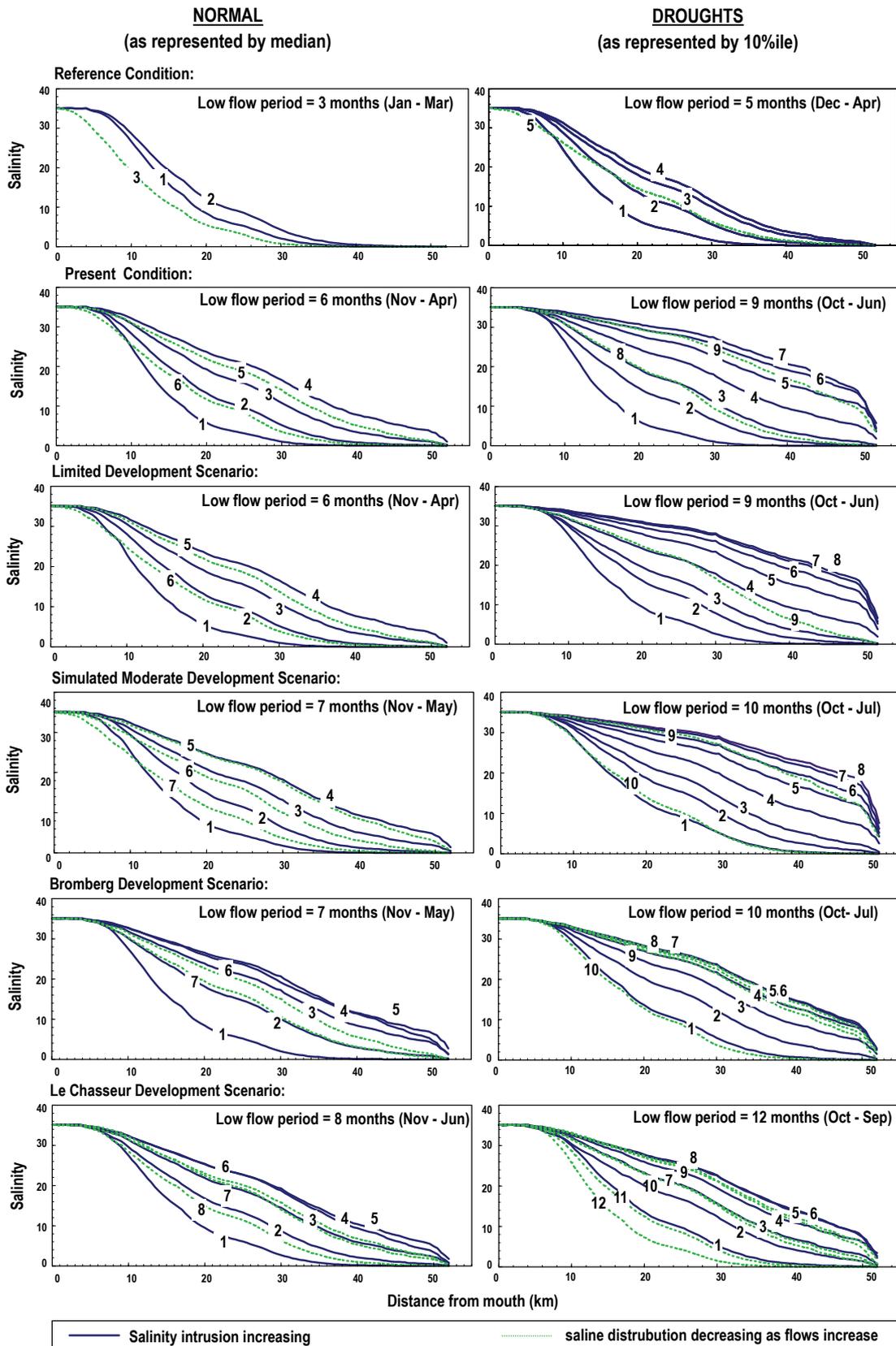


Figure B.5. Progressive saline intrusion during the low flow periods ( $< 10 \text{ m}^3 \cdot \text{s}^{-1}$ ) for the different scenarios (figure on lines indicate the number of months into the low flow period)

**TABLE B.4.** A summary of the average, as well as the maximum distances (in km), at which certain salinities penetrate during the low flow period ( $< 10 \text{ m}^3 \text{ s}^{-1}$ ) for the different runoff scenarios

Normal flows (median)			Droughts (10%ile)	
SALINITY (psu)	DISTANCE FROM MOUTH (KM)		DISTANCE FROM MOUTH (KM)	
	Average	Maximum	Average	Maximum
<b>Reference Condition:</b>				
30	7	9	9	11
20	12	14	15	20
10	19	22	26	31
<b>Present State:</b>				
30	9	12	11	22
20	16	26	25	42
10	28	37	39	None
<b>Limited Future Development:</b>				
30	9	12	12	23
20	16	26	27	43
10	28	37	41	None
<b>Moderate Future Development:</b>				
30	9	13	13	27
20	17	28	28	46
10	30	40	45	None
<b>Bromberg Future Development:</b>				
30	11	14	12	17
20	20	31	27	34
10	34	44	40	47
<b>Le Chasseur Future Development:</b>				
30	10	14	11	17
20	20	30	22	34
10	32	42	35	47

## Results

The future desired health of an estuary is determined by its present health as well as the estuary's importance. The Breede Estuary was deemed to be overall in a good condition (Present Status Category of B) and of high importance (Turpie *et al.*, 2002; Turpie, 2004). Therefore, according to the RDM methods, the future desired health of an estuary should be if present state or better (which was not possible due to current level of development in the catchment). According to the RDM methods, the 'acceptable future development scenario' is defined as the future runoff scenario, or a slight modification thereof, that represents the highest reduction in river inflow that will still maintain the aquatic ecosystem in the desired state. This evaluation must be done by a group of experts, e.g. at a workshop. Based on the above evaluations, the Limited Development Scenario was the only scenario that meets the flow requirements for the recommended state of the Breede Estuary. Therefore, the Reserve for Water Quantity to maintain the system in a good condition is estimated at  $954 \times 10^6 \text{ m}^3$  (53.4% of natural MAR). A summary of the flow distribution (mean monthly flows in  $\text{m}^3/\text{s}$ ) for the water quantity reserve is provided in Table B.6.

**TABLE B.6. Recommended reserve for water quantity for the Breede Estuary**

MONTH	1%	10%	20%	30%	40%	50%	60%	70%	80%	90%	99%
Oct	123.003	58.931	42.203	27.128	19.824	17.703	14.860	12.231	8.338	5.608	1.952
Nov	115.104	48.469	33.666	18.117	12.362	9.791	7.949	6.321	5.509	4.064	3.277
Dec	38.100	16.345	8.981	6.879	6.283	5.010	4.464	4.100	3.775	3.252	2.496
Jan	86.420	7.510	5.394	4.641	3.861	3.307	2.919	2.568	2.345	1.774	0.817
Feb	54.412	20.207	7.402	3.789	3.305	2.004	1.584	1.120	0.798	0.622	0.363
Mar	29.056	18.113	11.475	7.553	5.930	4.164	2.577	1.974	0.994	0.669	0.322
Apr	156.116	54.623	17.888	12.789	8.702	6.847	4.638	2.265	1.341	0.814	0.165
May	182.647	90.278	43.509	30.722	20.150	12.171	7.745	4.384	2.079	0.227	0.000
Jun	213.267	129.916	68.560	48.999	36.251	23.244	15.811	12.965	9.085	3.938	0.226
Jul	253.084	129.256	86.674	69.586	53.553	43.720	34.699	24.414	16.850	11.823	5.483
Aug	480.461	177.290	101.751	75.337	67.301	48.359	38.477	31.453	27.166	17.289	10.367
Sep	132.406	105.926	64.102	53.221	40.005	31.893	29.146	22.485	20.408	14.379	10.995

The overall confidence in the study results were medium (confidence = 60%), this was in no small measure due to the historical data gathered as part of an earlier field exercise (January 1996). If not for this data set, it might have been very difficult to calibrate the 1D model. Another contributing factor to the confidence attach to the study was the availability of relatively good daily river inflow data. This allowed for good calibration of the numerical model and gave a long term view of river inflow patterns in the months preceding the data collection exercises. In South Africa there is very few examples of river gauging stations close to the head of estuaries, in most cases the river inflow have to be simulated.

In the analyses of the simulated and measured average runoff that reached the estuary it became apparent that the river inflow often were much lower than that observed during the field exercises and two more hypothetical states were defined based on the modelling results to support the measured field data. The assistance of these states was later validated in salinity measurement taken on a number of occasions after the study was completed. This result highlights a number of the strengths of the study approach. Firstly, good quality data on the river inflow and the salinity distribution in relation to flow changes allowed for good numerical model calibration. Secondly, the long-term simulated runoff series in combination with numerical modelling results assisted in identifying the existence of additional hydrodynamic states. This method is therefore robust enough to provide a way to supplement short comings in the data collection process.

The interactive nature of the study allowed for the identification of important habitat drivers upfront or early on in the project execution, e.g. the REI zone (<10psu) and the start of the reed beds about 12 km. Changes that could affect these features could them be analysed in detail and summarised in a usable format for biologists participating in the study. The importance of establishing important habitat drivers or features as early on as possible in a multi-disciplinary study cannot be stressed enough, as this can prevent a significant amount of rework and add value to all components of the study. One important way in which to accomplish this is making it mandatory for all components to sample at the same time as his open the lines of communication between abiotic and biotic components.

Lastly, the ultimate goal of the hydrodynamics study was to develop an understanding of the long-term hydrodynamic processes operating in the Breede Estuary and how the processes might change under different flow scenarios. This understanding then needs to be communicated to the other specialists in the multi-disciplinary team. It is somewhat of an art form to balance the abiotic

specialists scientific understanding of long-term natural variability in estuarine hydrodynamics with the need to explain these changes to the biotic components without causing information overload. The summarising of relevant abiotic details in the hydrodynamic states facilitates this process. What is recognised upfront in doing so is that some processes are somewhat simplified, but the loss of detail is counter balanced by the fact that the evaluation are done in relation to a predicted reference condition and that the same assumptions are held for all scenarios (present and future). While the hydrodynamics specialist's may be intrigued by small tidal inconsistency, this information to a biotic specialist can be somewhat arbitrary, if not confusing, and best left in the appendixes.

Lamberth et al. (2008) provide more detail on how the abiotic states are used to derive at biotic condition.

# APPENDIX C

SUMMARY OF THE ABIOTIC STATES IDENTIFIED IN  
HISTORICAL ECOLOGICAL FLOW REQUIREMENTS  
STUDIES

## Summary of Abiotic States

### Permanently open estuaries

Estuary	Approach	Description of State	Flow regime
Olifants	1 D Modelling	Marine dominated	< 2 m <sup>3</sup> /s
		Saline penetration extended to middle reaches	2-5 m <sup>3</sup> /s
		Saline penetration limited to lower reaches	5-20 m <sup>3</sup> /s
		<b>Freshwater dominated</b>	<b>&gt; 20 m<sup>3</sup>/s</b>
Berg	3 D Modelling	Severe marine-dominated – saline intrusion extends further than 45 km upstream of mouth (i.e. into Zone D)	< 0.5
		Marine-dominated – saline intrusion extends up to 45 km from mouth (i.e. downstream of Zone D)	0.5-1.0
		Small to medium freshwater inflow – marine influence evident up to 33 km from mouth (i.e. downstream of Zone C)	1.0-5.0
		Medium to high freshwater inflow – marine influence only evident up to 12 km from mouth (i.e. downstream of Zone B)	5.0-25.0
		<b>Freshwater-dominated – estuary is fresh throughout (i.e. Zones A-D)</b>	<b>&gt;25.0</b>
Breede	1 D Modelling	Strongly Marine dominated, no REI zone	0-0.5 m <sup>3</sup> /s
		Marine dominated, variable REI zone	0.5-3 m <sup>3</sup> /s
		Marine and Freshwater influence balanced, well developed REI zone	3-10 m <sup>3</sup> /s
		Freshwater dominated, significant saline intrusion in lower reaches	10-20 m <sup>3</sup> /s
<b>Strongly freshwater dominated</b>	<b>&gt; 20 m<sup>3</sup>/s</b>		
Knysna	3 D Modelling	Marine-dominated, limited or no gradient	<0.5
		Marine-dominated, some gradient	0.5-2.0
		Marine-dominated state with small transition pulse	2.0-5.0
		Marine-dominated state with large transition pulse	5.0-10.0
		<b>Freshwater-dominated</b>	<b>&gt;10.0</b>
Keurbooms	1 D Modelling	Marine Dominated	< 0.5
		Saline with full salinity gradient	0.5-1.0
		Fresh with full salinity gradient	1.0-10.0
		<b>Freshwater Dominated</b>	<b>&gt; 10.00</b>
Sout	Conceptual	Marine Dominated	< 0.05
		Gradient	1.0-0.05
		<b>Predominantly fresh</b>	<b>&gt; 1.0</b>
Kromme	1 D Modelling	Marine	< 1
		Salinity Gradient	1-8
		<b>Fresh</b>	<b>&gt; 8</b>
Sundays	Conceptual, limited modelling	Marine dominated (fresh water influence limited to very upper reaches)	<0.5
		Small transition (freshwater front present in upper and middle reaches)	0.5-2.0
		Large transition condition (strong freshwater front present in middle and part of lower reaches) that revert back to a Small transition condition after the event	2.0-5.0
		<b>Freshwater dominated (estuary fresh throughout) that revert back to a Small transition condition after the event</b>	<b>&gt; 15.0</b>
Bushmans	Measured & conceptual	Marine Dominated – Salinity > 45 psu	< 0.05 longer than 12 months
		Marine Dominated – Salinity < 45 psu	< 0.05 Less than 12 months
		Small salinity gradient in the upper reaches (from about 24-30 km upstream from the mouth)	0.05-0.3
		Medium salinity gradient in middle and upper reaches (from about 15 km from the mouth)	0.3-1.0
		Medium pulse, salinity gradient develop in middle and lower	1.0-5.0

		reaches (from about 5 km from mouth)	
		Large Pulse, i.e. entire estuary is river or fluvial dominated for about a week	> 5.0
Nahoon	Conceptual	Predominantly marine	0-0.2
		Strong marine influence with a small salinity gradient near the head	0.2-0.5
		Well-defined longitudinal salinity gradient	0.5-2
		Strong freshwater influence with saline intrusion near the mouth	2-5
		Predominantly fresh (in the extreme completely flushed)	> 5
Mtata	Conceptual	Predominantly marine	0-0.5
		Salinity gradient present	0.5-2
		Salinity gradient present – Freshwater dominated	2-5
		Predominantly fresh	5-10
		Fresh	> 10

## Temporarily Open Estuaries

Estuary	State Descriptions	Flow range
Great Brak	Closed mouth	< 0.5 MCM
	Marine dominated with transition pulses	0.5-1 MCM (pulse releases)
	Transition	1-5 MCM
	Freshwater dominated	> 5 MCM
Goukamma	Closed mouth	< 0.5 m <sup>3</sup> /s
	Marine dominated	0.5-0.8 m <sup>3</sup> /s
	Transition	0.8-5.0 m <sup>3</sup> /s
	Freshwater dominated	> 5 m <sup>3</sup> /s
Tsitsikamma	Closed	< 0.05 m <sup>3</sup> /s
	Semi-closed	0.05-0.4 m <sup>3</sup> /s
	Open	> 0.4 m <sup>3</sup> /s
Tongati	Closed Mouth	<0.4 m <sup>3</sup> /s
	Mainly closed, occasional breached, open for a few days	0.4-0.6 m <sup>3</sup> /s
	Open mouth, seawater intrusion. Brief closures of a few days sometimes in lower range	0.6-5 m <sup>3</sup> /s
	Open Mouth, river dominated	>5.0 m <sup>3</sup> /s
Mdloti	Closed, where the estuary is cut-off from the sea with no water exchange.	0-0.3 m <sup>3</sup> /s
	Semi-closed, with no seawater intrusion (except occasional over-wash), but with water still flowing out to sea	0.3-2.0 m <sup>3</sup> /s
	Open, with seawater intrusion	2.0-5.0 m <sup>3</sup> /s
	Open, with no seawater intrusion, i.e. completely fresh	> 5.0 m <sup>3</sup> /s
Siyaya	Closed Mouth, low water levels	0-0.025 m <sup>3</sup> /s
	Closed Mouth, high water levels	0.025-0.3 m <sup>3</sup> /s
	Open Mouth (1-3 days at a time)	> 0.3 m <sup>3</sup> /s
Matjies	Mouth Closure (> week)	< 0.03 m <sup>3</sup> /s
	Intermittent Mouth Closure (<1 day)	0.1-0.03 m <sup>3</sup> /s
	Mouth Open	> 0.1 m <sup>3</sup> /s
Kleinemonde	Closed Mouth	Flow Volume < 0.3 x 10 <sup>6</sup> m <sup>3</sup> and cumulative inflows < 0.3 x 10 <sup>6</sup> m <sup>3</sup>
	Intermittently open/closed driven by persistent low flow periods	Flow Volume < 0.3 x 10 <sup>6</sup> m <sup>3</sup> and cumulative inflows > 0.3 x 10 <sup>6</sup> m <sup>3</sup>
	Intermittently open/closed driven by high flow events	Flow Volume > 0.3 x 10 <sup>6</sup> m <sup>3</sup>
Mhlanga	1: Predominantly Closed	< 0.4 m <sup>3</sup> /s
	2: Predominantly Semi-closed	0.4-0.5 m <sup>3</sup> /s

	3: Predominantly Open, with marine influence 4. Predominantly Open, fresh water dominated	0.5-5 m <sup>3</sup> /s > 5 m <sup>3</sup> /s
Mdloti 002	Closed, where the estuary is cut-off with no exchange.	0-0.3 m <sup>3</sup> /s
	Semi-closed, with no seawater intrusion	0.3-2.0 m <sup>3</sup> /s
	Open, with seawater intrusion	2.0-5.0 m <sup>3</sup> /s
	Open, with no seawater intrusion, i.e. completely fresh	> 5.0 m <sup>3</sup> /s
Orange	Closed, for extended period	< 10.0 m <sup>3</sup> /s
	Predominantly Open, with marine influence	10.0-50.0 m <sup>3</sup> /s
	Open, river dominated	> 50 m <sup>3</sup> /s
Palmiet	Closed	< 0.05 m <sup>3</sup> /s
	Semi-closed	Usually when flows < 1 m <sup>3</sup> /s
	Open (with extensive sea water intrusion)	1-10 m <sup>3</sup> /s
	Open (with limited seawater intrusion on the flood tide and strong river influence)	10-20 m <sup>3</sup> /s
Tukhela	Open (with no seawater intrusion and very strong river influence)	>20 m <sup>3</sup> /s
	Mouth closed, from weeks to a few months at a time	0-2 m <sup>3</sup> /s
	Mouth open, occasional mouth closures of a few days	2-5 m <sup>3</sup> /s
	Mouth open, saline intrusion	5-30 m <sup>3</sup> /s
	Mouth open, river dominated	> 30 m <sup>3</sup> /s

# APPENDIX D

## EWR DATA REQUIREMENTS

## EWR DATA REQUIREMENTS

**Problem:** *Historically there was no standardized approach to identifying and measuring the parameters that need to be monitored for the RDM.*

**Response:** *The estuary community conducts a national workshop to develop standardised resource monitoring procedures for estuaries through for specific application in the Ecological Reserve determination and implementation process (Taljaard et al., 2003).*

The section below provides a summary of the current data requirements to conduct an environmental flows assessment as part of an RDM project. The section reflects the findings of Water Research Commission Report No. 1308/1/03 (Taljaard et al., 2003) as captured in DWA 2008, with some minor adaptations made to spatial and temporal scales based on experience gained over the last decade

### 13.3 DATA REQUIREMENTS ON HYDROLOGY

#### 13.3.1 SIMULATED RUNOFF DATA

Data to be simulated by standard hydrological models for Reference Condition, Present State and a range of future run-off scenarios covering a range of flow reductions from present to worst case is required. Flows should be representative of inflow at head of estuary. This data is required to estimate seasonal variability in river flow patterns (the accuracy and confidence limits of the simulations must be indicated). Data should be simulated over a 50-80 year period, provided as average monthly flows, to allow for investigations into event scale (e.g. droughts and floods). Daily flows may at times be required to highlight changes in small catchments.

#### 13.3.2 FLOOD HYDROGRAPHS

Flood hydrographs need to be simulated for the 1:1 to 1:200 year floods for Reference Condition, Present State and a range of future run-off scenarios. This level of information is usually only required on for high confidence studies or where there is major dam(s) development at present in the catchment or being planned in future. Flows should be representative at the head of the estuary and provided as hourly flows over the flood period. In the case of lower confidence studies the reduction in floods should be estimated based on expert opinion (preferably study hydrologist)

### 13.4 DATA REQUIREMENTS ON SEDIMENT DYNAMICS

Understanding the sediment process is underlying to all hydrodynamics processes as it influences mouth state, flushing times and provides insights on how an estuary operates under longer time scales. It may not be possible to acquire these data sets in the short term, but long term monitoring programmes to collect such data must be considered if the dynamic sediment processes in estuaries are to be better understood. Sediment process are generally not surveyed or analyzed in detail for low to medium confidence studies, i.e. studies that do not involve major water resources developments. These are mostly relevant on available data which is in very short supply for most South African estuaries.

The disturbance of the sediment erosion/deposition equilibrium in an estuary can lead either to siltation, resulting in the estuary becoming shallower, or it can lead to the erosion of important

sediment habitats. Under natural conditions many estuaries were probably in a state of long-term equilibrium of sedimentation and erosion. However, this equilibrium can be disturbed because of changes in run-off, especially if the occurrences and magnitudes of major floods are changed.

Floods and, in some cases, high seasonal flows can influence the sediment erosion/deposition equilibrium. Floods can alter important features within an estuary, such as the bathymetry (e.g. channel depth or the size of intertidal areas) and sediment composition (e.g. sand or mud).

#### 13.4.1 BATHYMETRIC/TOPOGRAPHICAL SURVEYS

Surveys should be conducted using Differential Global Positioning System (D-GPS) and echo-sounding to monitor berm height, mouth sediment dynamics and cross section profiles upstream of the mouth.

The mouth region should be surveyed intensively, i.e. 10 to 50 m interval depending on the size of the estuary and variability in bathymetry. Upstream cross-section profiles should be taken along entire estuary at 500 m to 1000 m intervals. How often surveys need to be repeated will depend on the time scales of the dominant sedimentation/erosion processes in an estuary – typically varying between 1 and 5 year intervals, with a minimum record of about 15 years. Alternatively, numerical models can be used to simulate longer-term processes.

This data are required to establish a baseline data set of the topography, particularly if numerical hydrodynamic modelling is to be used in estimating Reference Condition and the implication of future scenarios. Typically data older than 5 years should not be used, as well as data collected prior to a major flood. The data can also be used to calculate the volume of the estuary and give an indication of flushing times.

#### 13.4.2 SEDIMENT GRABS

Grab samples should be collected using a Van Veen or a Zabalocki-type Eckman grab (to characterize recent sediment movement) for particle size analyses. Samples should be taken along entire estuary at 500 to 1 000 m intervals Sediment grabs: Seasonal sampling should be conducted (spring, summer, autumn and winter) for one year to assist with understanding temporal changes and responses to seasonal flow patterns.

#### 13.4.3 SEDIMENT CORES

Core samples should be collected using a corer (for historical sediment characterization). Intervals similar to cross-section profiles are recommended. This is a once-off survey procedure.

#### 13.4.4 SEDIMENT LOAD AT HEAD OF ESTUARY

To allow for an improved understanding of the sediment process (erosion or accretion) and its impact on water quality (e.g. turbidity, water clarity) the sediment load at head of estuary should be sampled daily for a minimum 5 years. Analyses should include the detritus component – particulate carbon/loss on ignition.

## 13.5 DATA REQUIREMENTS ON HYDRODYNAMICS

### 13.5.1 CONTINUOUS FLOW RECORDING OF RIVER INFLOW

Data on river inflow into an estuary are crucial for correlating river flow to the state of the mouth (as reflected by water level recordings), particularly in temporarily open/closed estuaries. The dataset duration required will depend on, for example, the frequency of mouth closure in the particular estuary. A flow gauging station should be installed to measure river inflow near the head of estuary. In requesting continuous flow, the request is not for gauging weirs to be constructed at the top of each estuary as such, but rather that flows be monitored in appropriate ways that will not disturb migration of aquatic biota. If this is not possible models should be developed to simulate daily inflows to the estuary based on catchment characteristics and daily rainfall data.

### 13.5.2 CONTINUOUS WATER LEVEL RECORDINGS

A continuous water level recorder should be installed at the mouth of the estuary to obtain long-term records of variations in tidal levels and mouth conditions. Continuous water level recordings are currently not available for most estuaries, resulting in EF assessments being based on limited visual observations of tidal variation (i.e. over at least 2 tidal cycles) with much lower confidence. It is therefore strongly recommended that water level recorders be installed, especially since 5-15 years of data are required for the high confidence studies. Continuous flow recordings (gauging station) of river inflow at the head of estuaries and continuous water level recording at estuary mouths (and mouth observations) require longer-term data sets and it is therefore necessary to start such baseline monitoring programmes well in advance (at least 5 years) of a EF study. In this regard it is recommended that the DWA implement such monitoring activities timeously in South African estuaries, particularly those earmarked for substantial water abstraction in future.

### 13.5.3 DAILY MOUTH OBSERVATIONS

Where possible, daily mouth observations should be logged in temporarily open/ closed estuaries and particularly in systems where sometimes a semi-closed mouth phase exists. The time at which the observation was made and the state of the tide must also be recorded, ideally at low tide. This data is needed to obtain long-term records of variations in mouth conditions and the estuaries responses to flow changes.

### 13.5.4 WATER LEVELS ALONG ESTUARY

In very long systems and where EF studies requires numerical modelling, water levels data must also be collected along the length of the estuary, either using continuous water level recorders or water level gauging poles and manual observations. Data should be collected at 2-6 stations along estuary depending on the length of the estuary. These should preferably be undertaken during an above average spring and neap tide. These are critical requirements for permanently open estuaries where numerical modelling are used to predict change in the salinity profile.

### 13.5.5 WAVE CONDITIONS

This information is used to correlate mouth closure with possible storms at sea (as reflected by the direction and amplitude of the waves). Available data should be accessed, but no measurements are specified as part of a baseline monitoring.

### 13.5.6 AERIAL PHOTOGRAPHS

Aerial photographs can provide a first estimate in terms of the dynamic of an estuary mouth, for example, to derive the effect of wave action on the mouth dynamics, in particular, the extent to which the mouth is exposed to direct wave action, and to determine the width of the breaker zone (indicative of the beach slope).

Full colour geo-referenced rectified aerial photographs 1: 5 000 scale aerial photography surveys should be done annually. Data should be made available in a digital format. The photographs should be vertical (not oblique because that distorts observations). The photographs should be up to the head of the estuarine systems and must include the breaker zone near the mouth. Surveys should be conducted at low tide preferably in summer as it shows colour differentiation between vegetation types better.

## 13.6 DATA REQUIREMENTS ON WATER QUALITY

While water quality do not form explicitly form part of the discipline of hydrodynamics, but parameters measures as part of water quality surveys informs, and are in turn, informed by hydrodynamics process in estuaries. Therefore the hydrodynamic component is strongly reliant on data collected as part of this component. Salinity is the primary indicator of mixing processes. These measurements, together with the river inflow data (must be collected simultaneously) are used to estimate the correlation between salinity/temperature distribution patterns along the length of the estuary and river flow. Where only a limited amount of fieldwork is possible, this could best be achieved by measuring the two 'extremes', i.e. end of low flow season and the peak of high flow season.

The water quality field exercise must coincide with the salinity/temperature profiling. In this way a limited water quality data set (which is usually very expensive to acquire) can be used to derive water quality characteristics under different tidal conditions, using salinity data, expert opinion or appropriate assessment tools, e.g. numerical models. Where effluent discharges occur into the estuary, i.e. below the head of the estuary, these have to be sampled as well.

The analytical techniques used in the processing of marine and estuarine water quality samples vary greatly inform those used in the analysis of fresh water samples. It is therefore crucial that the analyses of water quality samples be conducted by an accredited marine analytical laboratory.

While toxic pollutants need to be monitored to understand the water quality status of an estuary, it does not inform hydrodynamic process understanding and the data collection protocol are therefore disregarded in this document.

### 13.6.1 WATER QUALITY OF RIVER INFLOW

System variables (pH, DO, turbidity, suspended solids, TDS and temperature), nutrients (inorganic nitrogen [nitrite, nitrate and ammonia], reactive phosphate and silicate) and toxic substances (where relevant) should be measured. Particulate organic matter, although not measured on a regular basis

by DWAF should be provided if available. To achieve a high level of confidence, a monthly data record for a minimum of 5-years is required.

### 13.6.2 WATER QUALITY IN ESTUARY

The water quality samples should be collected on salinity and temperature and system variables (pH, DO, turbidity, suspended solids). Information on inorganic nutrients (nitrate/nitrite, ammonia, reactive phosphate, total phosphorus) also provides important information on flushing times and regions of retention in an estuary.

Salinity and temperature data must be collected at 0.5 m depth intervals, while other water quality parameters are collected in surface and bottom waters. At stations deeper than 10 m, a sample at an intermediate depth may also be required (site specific decision). In small estuaries (< 5 km long) stations should be distributed geographically along the entire estuary with a minimum of 5 sites. In larger estuaries (> 5 km long) stations should be distributed geographically along the entire estuary at fixed intervals. A rough estimate for setting the distance between stations is to divide the length of the estuary by 10 (i.e. if an estuary is 30 km long, the distance between stations should be about 3 km). Typically a representative number of stations for longer estuaries are between 10 and 15. Sampling should cover all the salinity regimes. In systems with large cross sectional areas, sampling stations should also be selected along cross sections. During each sampling survey, water quality samples must also be taken in the river and in the near-shore marine waters (i.e. the water sources).

To be of value sampling should occur at least once during a low flow and a high flow season. For temporarily open/closed systems, a stable closed phase must be sampled as well as a stable open phase. For higher confidence studies sampling should be conducted seasonally, (i.e. during spring, summer, autumn and winter) with river inflow being representative of a particular season covering the different abiotic states. In systems where the semi-closed phase or overwash is important, these states need to be sampled. If it is only possible to do one survey, this should be done at the end of the low flow season, particularly for permanently open estuaries.

### 13.6.3 EFFLUENT DISCHARGES:

Effluent discharges should be measured at the end of the pipe just before entering the estuary. In addition to flow rate, other parameters that need to be monitored will depend on the composition of the effluent. Effluent discharges are licensed under the National Water Act where operators are required to monitoring effluent volume and composition. Monitoring generally occur at daily or weekly intervals, depending on the variability in effluent composition overtime.