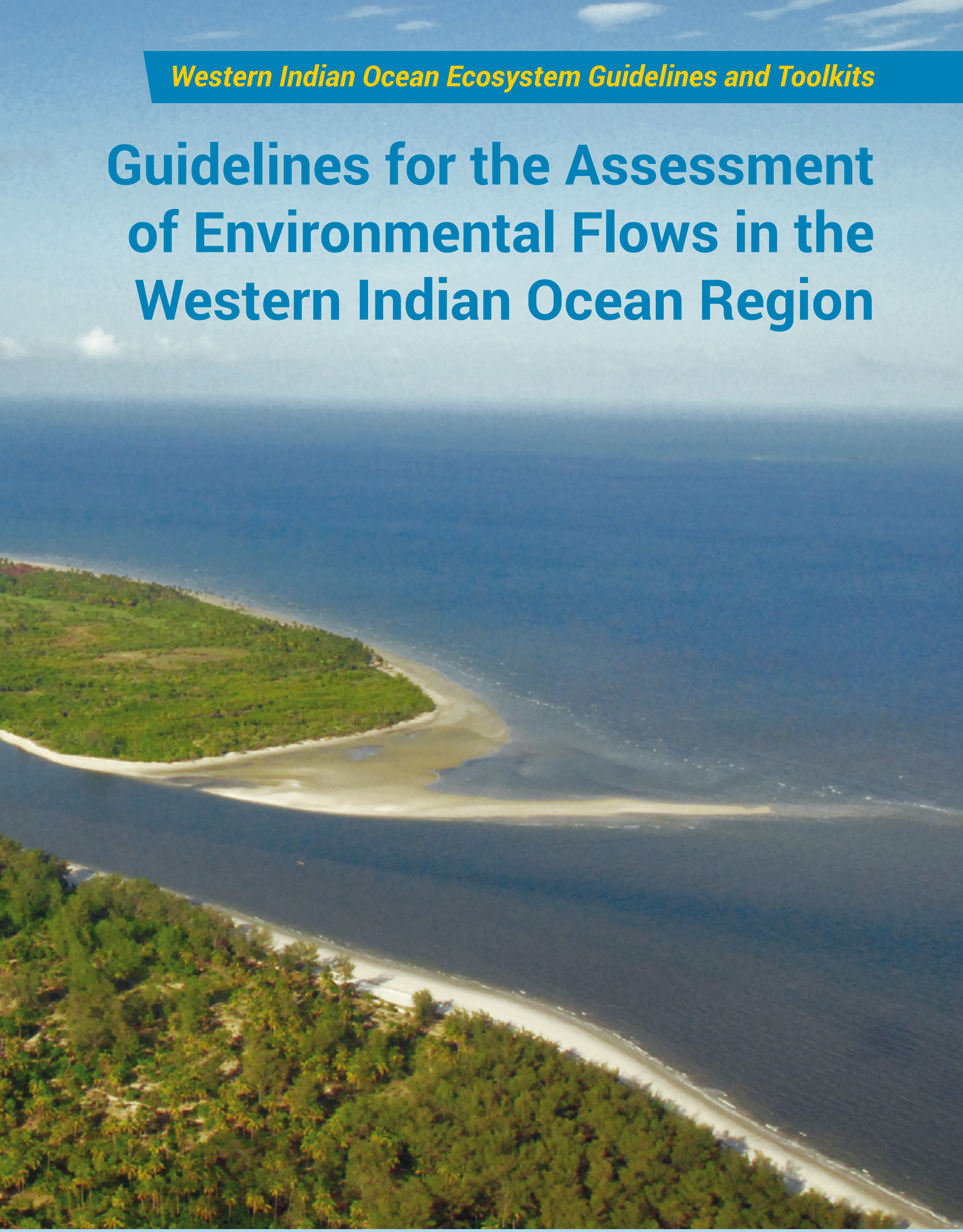


Western Indian Ocean Ecosystem Guidelines and Toolkits

Guidelines for the Assessment of Environmental Flows in the Western Indian Ocean Region

Western Indian Ocean Ecosystem Guidelines and Toolkits

Guidelines for the Assessment of Environmental Flows in the Western Indian Ocean Region

Published by the United Nations Environment Programme/Nairobi Convention Secretariat.

Disclaimer:
This publication has been produced by the United Nations Environment Programme-Nairobi Convention and WIOMSA with the kind assistance of various regional governments, Non-Governmental Organizations, Civil Society Organizations, as well as of individuals through the Global Environment Facility (GEF) funded WIOSAP project and SIDA funded MASMA project executed by the Convention and WIOMSA respectively. The report is copyrighted entirely to the Nairobi Convention and WIOMSA.

Compiled and prepared by:
Cate Brown and Jackie King, with contributions from Lara Van Niekerk and Susan Taljaard.

Series Editor:
Matthew D. Richmond

Designed by:
Marco Nunes Correia

Coordinated by:
Jared Bosire, Julius Francis and Timothy Andrew

Citation:
UNEP-Nairobi Convention/WIOMSA (2020). Guidelines for the Assessment of Environmental Flows in the Western Indian Ocean Region. UNEP, Nairobi, 79 pp.

Western Indian Ocean Ecosystem Guidelines and Toolkits
ISSN: 2714-1942

Table of Contents

List of Tables

List of Plates

List of Figures

List of Boxes

Preface

The Western Indian Ocean (WIO) region has several important river basins whose runoff drains to the ocean through estuaries and deltas. In many instances, poor management of river basins has resulted in changes to river flows, degradation of water quality and changes in sediment loads. These hydrologic alterations are now impacting critical coastal and marine ecosystems, leading a reduction in ecosystem goods and services that support the livelihoods of coastal communities, as well as national economies. The Integrated Water Resources Management (IWRM) approach that some of the countries in the WIO region have adopted through reforms in their water sectors follows a holistic approach to the management of water resources. However, capacity for IWRM implementation in most of the participating countries has been limited by lack of appropriate decision-making tools for allocating water to various users including water allocation (Environmental Flows, or EFLows) for sustaining ecological systems that include coastal and marine ecosystems.

To remedy deficiencies in the management of river basins, the the Global Environment Facility-funded Western Indian Ocean Strategic Action Programme (WIOSAP) project proposed to focus on building capacity for EFlows Assessments and implementation in the region. EFlows Assessments are an important decision support tool for the management of river flows because it allows for informed allocation of river water resources while at the same time allowing adequate volume and appropriate timing of river flow to reach the downstream areas where it is required to maintain aquatic and terrestrial ecosystems. The application of EFlows Assessments is still underdeveloped in most countries in the WIO region at a time when anthropogenic influences on river basins are greater than ever. Consequently, awareness on the value of EFlows Assessments needs to be created and capacity for its implementation developed.

To facilitate capacity building in and promotion of EFlows Assessments as a tool in IWRM in the region, the Nairobi Convention, in collaboration with the WIO Marine Science Association (WIOMSA), have supported the development of these *Guidelines for the Assessment of Environmental Flows (EFlows) in the Western Indian Ocean region*. The *Guidelines* are practical and concise and are designed for adoption and direct application by River Basin/Water Management Authorities and other EFlows practitioners in the region.

The inclusion of comprehensive descriptions of what EFlows Assessments are, methods that can be used, practical steps needed to carrying out an assessment, and how to make sure that the outputs of assessments are useful and taken up at management, governance and policy levels makes this resource an essential addition to the tools available to address pressing environmental needs in the WIO region.

The development of the *Guidelines* has followed a process that has resulted in them being endorsed by the countries of the WIO region, an important aspect if they are to be actively utilized in the region. They provide a practical resource that will allow countries to build on experiences from elsewhere in the region and the world and enhance the quality and standard of ecosystem assessment and monitoring in the WIO.

I encourage practitioners in the WIO to make use of this resource and to actively contribute to improving and updating the *Guidelines* based on experiences gained through the WIOSAP demonstration projects. I would like to congratulate all those that have been involved in their collaborative development and have no doubt that these *Guidelines* will be of great use in the future.

Kerstin Stendahl
Head of Branch
Ecosystems Integration Branch,
Ecosystems Division
United Nations Environment Programme

Acronyms and abbreviations

BBM	Building Block Methodology
CASiMiR	Computer Aided Simulation Model for Instream Flow and Riparia
DRIFT	Downstream Response to Imposed Flow Transformation
EEFAM	Estuary Environmental Flows Assessment Methodology
EFlows	Environmental Flows
EFMP	Environmental Flows Management Plan
ELOHA	Ecological Limits of Hydrological Alteration
HEC-EFM	Hydrologic Engineering Center-Ecosystem Functions Model
HFSR	Habitat-Flow-Stressor-Response
HPP	Hydropower Project
IFIM	Instream Flow Incremental Methodology
IUA	Integrated Units Analysis
IWRM	Integrated Water Resource Management
MAR	Mean Annual Rainfall
PSC	Project Steering Committee
Q95	95th percentile on a Flow Duration Curve
RSA	Republic of South Africa
SDGs	Sustainable Development Goals
SEFA	System for Environmental Flows Analysis
SUA	Sokoine University of Agriculture
ToRs	Terms of Reference
TxEMP	Texas Estuarine Mathematical Programming
VEC	Valued Ecosystem Component
WIO	Western Indian Ocean
WIOMSA	Western Indian Ocean Marine Science Association
WIOSAP	Western Indian Ocean Strategic Action Programme
ZAMWIS	Zambezi Water Resources Information Systemw

Acknowledgements

The authors wish to acknowledge the research conducted by Dirk Campher to support the section on trends in EFlows Assessments in the WIO region. We also thank the members of the EFlows Task Force for the WIOSAP and the Nairobi Convention Secretariat for their guidance and comments on review. The funding received from the Global Environmental Facility (GEF) funded WIOSAP project is gratefully acknowledged, as are the expert reviewers who gave of their time to ensure that a comprehensive and acceptable product resulted from this work. Finally, WIOMSA through the MASMA project is thanked for their input in managing the development of the draft Guidelines and final preparation of the document for publication.

The Guidelines will be hosted by the Sokoine University of Agriculture (SUA) United Republic of Tanzania, who will be responsible for future dissemination and any necessary reviews in collaboration with the Nairobi Convention and other relevant partners in the region.

Photo credits: Cate Brown (plate 4), Hans Beuster (plate 8), Karl Reinecke (plates 1, 5 and 9), Matthew D. Richmond (plates 2, 3, 6, 7 and cover photo).

1. Introduction

These *Guidelines* for the Assessment of Environmental Flows (EFlows) in the Western Indian Ocean (WIO) region form part of the deliverable for the project entitled Implementation of the Strategic Action Programme for the protection of the WIO from land-based sources and activities (WIOSAP). The Project is being implemented and executed through a Partnership Approach, with the United Nations Environmental Programme (UNEP) Nairobi Convention Secretariat as the Executing Agency. The participating countries include Comoros, Madagascar, Mauritius, Seychelles, Mozambique, Kenya, Tanzania, France, Somalia and South Africa. The goal of WIOSAP is to: '*Improve and maintain the environmental health of the region's coastal and marine ecosystems through improved management of land-based stresses*'. The specific objective of WIOSAP is: '*To reduce impacts from land-based sources and activities and sustainably manage critical coastal-riverine ecosystems through the implementation of the WIOSAP priorities with the support of partnerships at national and regional levels.*'

There are four components to the Project:

1. Protection, restoration and management of critical coastal habitats and ecosystems;
2. Improvement of water quality;
3. Sustainable management of river flows, including building capacity for EFlows Assessments and implementation; and
4. Strengthening governance and awareness.

This document *Guidelines for the Assessment of EFlows in the WIO region* is part of the activities of Component 3.

1.1 Background to the development of the Guidelines

The *Guidelines for the Assessment of EFlows in the Western Indian Ocean Region* are intended to provide guidance on EFlows Assessments for rivers and estuaries (excluding groundwater contributions directly into the marine environment) with a view to enabling a harmonized approach to such assessments across the region in order to enhance protection of the WIO. The document is intended for use by government agencies responsible for river basin management, national research institutions, regional organizations and civil society organizations playing a role in the management of water resources.

The need for these *Guidelines* arose due to the recognition that although EFlows Assessments is an important decision support tool for the management of river flows, which impact downstream coastal and marine ecosystems, its application is still underdeveloped in most countries in the WIO region. Countries in the WIO differ in the number and sizes of river catchments, and consequently their needs and the level of assessment required or achieved, as well as in the resources and capacity available to carry out effective assessment and monitoring varies. It was recognized that a standardized tool, together with an awareness and capacity building process, would be helpful in encouraging the uptake in relevant policy and governance processes. Such a standardized approach would enable learning and cross-fertilization between the countries of the region. The demonstration projects supported by the WIOSAP provide a unique opportunity to test the *Guidelines* and to improve on them before potential broader use in other areas of the WIO.

It is recognised that several excellent documents providing advice and guidelines for assessment of EFlows have been developed in recent years. However, although many approaches and tools for EFlows Assessments are fairly universal in their potential application, it is important to note that the particular relevance, utility or practicality of one versus another is determined by the specific local context. For example, countries of the WIO differ in the availability of data or in terms of access to the capacity required for EFlows. Governance influence on the potential use of EFlows also varies across the WIO (it is recognized that some WIO island states, such as Seychelles or Mauritius, have relatively little need for comprehensive EFlows Assessments).

The objective of preparing WIO-specific guidelines on EFlows is therefore to help users in the region to focus on what is most likely to work for them and to assist them to better match the vast array of available tools and approaches to their particular situation. Guidelines such as these provide a regional standard so that regional objectives of marine and ocean management can be addressed in a harmonized manner.

The process followed in the development of these *Guidelines* was rigorous and was initiated in April 2018 at a meeting of the Nairobi Convention Focal Points in Madagascar. The need for various guidelines and the process to be followed in their development was discussed. As a first step, the Secretariat was requested to prepare Terms of Reference (ToRs) for a consultant to develop a working draft of these *EFlows Guidelines*. These ToRs were approved by the Project Steering Committee (PSC) at a meeting in Kenya held in August 2018, and a consultant was recruited in the 3rd quarter of 2018. Progress on the process was reported to a meeting of Focal Points and regional experts in December 2018 in Mozambique, while active development of the *Guidelines* proceeded from January 2019. This included consultation with regional experts and review of the draft *Guidelines* by the Secretariat and Contracting Parties. The *Guidelines* were validated during the Science to Policy meeting comprising of Focal Points, experts and partners in May 2019 during which further technical and policy input were given. The updated *Guidelines* were launched at the PSC meeting held in June 2019, which approved: (i) adoption for wider regional application; (ii) testing, especially by river basin and water management authorities; (iii) revision as appropriate after testing, subject to feedback from different stakeholders; and (iv) implementation of capacity building efforts to promote EFlows as a tool in integrated water resource management. The PSC approvals were followed by professional editing, layout/design, publication and dissemination.

Plate 1. Sampling macro-invertebrate in the Zambezi River.

1.2 Structure of the Guidelines

The *Guidelines* outline the objectives of the WIOSAP project and the process involved in its development (this Section) and introduce the concept of EFlows (Section 2). They then focus on EFlows Assessments through Section 3 which describes and compares EFlows Assessment methods and the information provided by each; followed by Section 4 where more detail on undertaking an EFlows Assessment is provided, and Section 5, which discusses issues associated with managing data limitations. Finally, Section 6 provides guidance on mainstreaming EFlows, in particular building technical capacity in EFlows Assessments.

1.3 Definitions

Key definitions used in these *Guidelines* are:

- EFlows: The magnitude, frequency, timing, and quality of water and sediment flows necessary to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (amended from Brisbane Declaration, 2007).
- Riverine ecosystems: Flowing waters that drain the landscape, and include the biotic (living) interactions amongst plants, animals and micro-organisms, as well as abiotic (non-living) physical and chemical interactions of its many parts (Angelier, 2003). For the purposes of this document, river ecosystems also include riparian wetlands and lakes, and floodplains.
- Estuarine ecosystems: Semi-enclosed coastal bodies of water that are connected to the sea either permanently or periodically, have a salinity that is different from that of the adjacent open ocean due to freshwater inputs, and include a characteristic biota (Whitfield and Elliot, 2011). During floods, an estuary can become a river mouth with no seawater entering the formerly estuarine area or, when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become fresh or even hypersaline. For the purposes of this document, the definition excludes bays or lagoons that have no river inflows but receive land-based freshwater from aquifers or groundwater seepage.
- Marine ecosystems: Aquatic ecosystems that are characterized by waters with a high salt content. Marine ecosystems encompass oceans, salt marshes and intertidal areas, estuaries and lagoons, mangroves and coral reefs, the deep sea and the sea floor. For the purposes of this document, however, marine ecosystems refer to nearshore and inner (coastal) continental shelf marine ecosystems and exclude estuaries, mangroves and lagoons (which are dealt with separately) and deep-water oceanic ecosystems (which are excluded) (after van Ballygooyen *et al.*, 2007).

2. Environmental Flows

Rivers, aquifers, estuaries, coastlines and oceans are inter-connected and inter-dependent ecosystems that are linked through the flow of water, sediment, nutrients and biota and collectively store, clean and protect the Earth's water. They are complex, multi-dimensional ecosystems that are supported by a wide array of interactions that differ in timing and quantity.

The Earth's aquatic ecosystems provide a host of ecosystem services to people, including nutrient cycling, soil formation and primary production (supporting services); freshwater, sand and gravel, wood and fibre, fuel, food and medicines (provisioning services); climate regulation, flood regulation, disease regulation and water purification (regulating services); and aesthetic, spiritual, educational and recreational aspects (cultural services) (MEA, 2005). These ecosystem services support life, health and livelihoods in urban and rural areas (Figure 1) and provide shelter and security from hunger, natural disasters and diseases. Ensured access to these services promotes well-being, social cohesion, cultural diversity, goodwill and altruism; it also supports property values and national economies.

According to the World Resource Series (WRI, 2001), coastal habitats alone account for approximately 1/3 of all marine biological productivity, and estuarine ecosystems are among the most productive regions on the planet. Thus, it follows that human-driven changes, which negatively affect these ecosystems, harm people at the practical level and at deeper psychological and social levels.

2.1 The need for EFlows

The concept of EFlows evolved from a growing global concern over degrading rivers and estuaries and a need to mitigate the effects of human development by managing water resources for long-term sustainability (Richter, 2009). When established in a structured way, the EFlows approach ensures development does not undermine the ability of these ecosystems to function sustainably and enhances their resilience to cli-

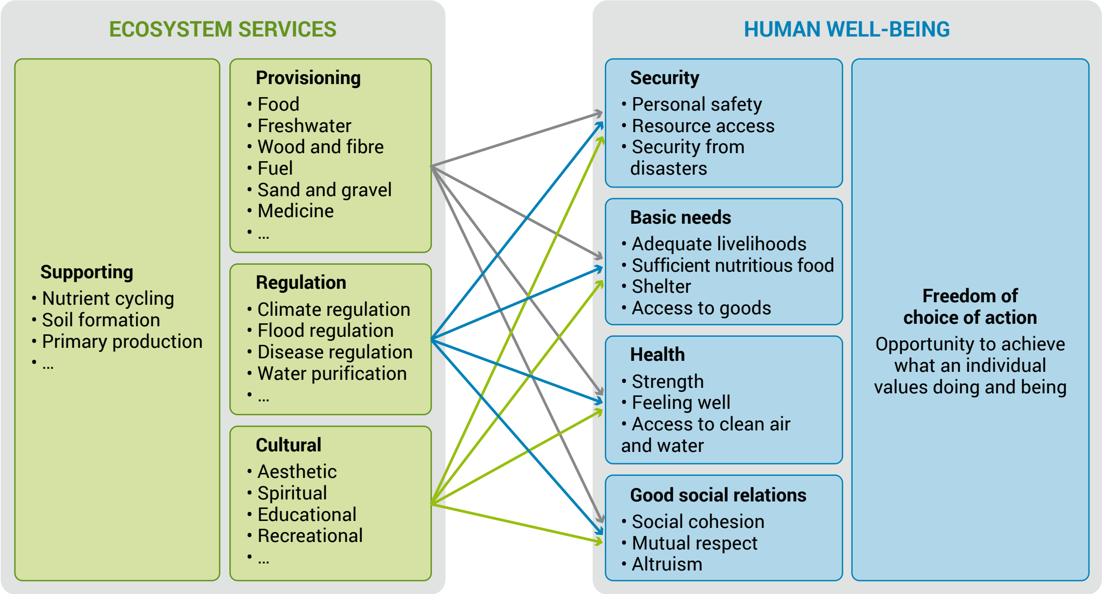


Figure 1. Ecosystem services and links to human well-being (MEA, 2005).

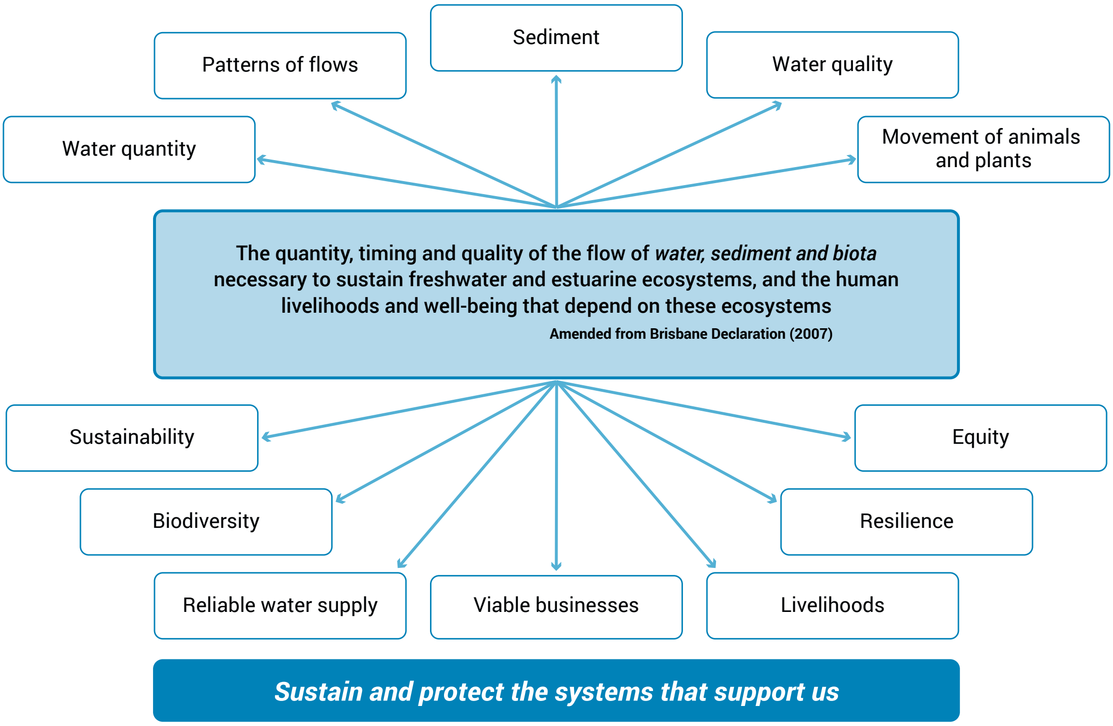


Figure 2. Environmental Flows are the water quantity, quality, pattern of flow and more (above the box) that are necessary to support human livelihoods and wellbeing (below the box).

mate change. The ecosystems can then continue to provide ecosystem services of value to people into the future (Figure 2).

Scientists provide expert advice on how river and estuarine ecosystems will change under various water and sediment flow and quality conditions through the EFlows Assessment process (top of Figure 2), and stakeholders use this information to decide what each river or estuary should be used for and what level of protection it will be afforded (bottom of Figure 2). Several countries are developing processes to do this second part; in South Africa it is achieved via a process called Classification (Box 7, Section 6.4).

2.2 The effects of human developments on rivers and estuaries

Rivers, estuaries and, ultimately, marine ecosystems receive water, sediments and chemicals from drainage across the landscape. The quality, volume and timing of these inputs profoundly affect the ecosystems' character and ecological condition, and so they are highly susceptible to landscape changes driven by human activities. Changes in land cover affect hydrological processes such as evapotranspiration, interception, infiltration and percolation, which change the volume, timing and chemical composition of runoff (Petersen *et al*., 2017) and thus the physical, chemical and biological processes in the receiving water bodies (Tong and Chen, 2002). Inappropriately located dams and/or dams with poorly-designed operating rules affect many of the aspects of the flow regime and thus the efficient functioning of rivers, estuaries and the ocean (Figure 3). Aspects that can be affected include the dry season flows, the onset and duration of hydrological seasons, the volume and timing of floods and the variability of the flow regime.

Changes in any of these have knock-on effects on the ecological condition of the affected ecosystems and the ecosystem services they provide. Reduced wet season floods, for instance, decrease or halt inundation of floodplains, detrimentally affecting and perhaps annihilating the life cycles of fish and other organisms dependent on these areas for breeding and feeding. Reduced dry season flows leave the river ecosystem more vulnerable to fluctuations in ambient temperature, which may have severe repercussions for fish, for example, in very hot or very cold climates.

Human activities at the catchment scale may increase the levels of sediment and pollutants entering the aquatic ecosystem and, through removal of riparian vegetation, wetlands and floodplains, reduce its capacity to store floods and recharge groundwaters. In-channel modifications such as dams that trap sediments that would normally move along the system, navigation projects, and mining for sand and heavy minerals further reduce the capacity of the ecosystem to function efficiently (McNally and Mehta, 2004). Excessive sediments draining in from the landscape can block light needed for growth of aquatic plants, harm fish gills, silt up important habitats, decrease open water areas, block irrigation systems and reduce visibility needed for feeding. Conversely, reduced sediment as a result of trapping in dams and weirs can lead to bank and bed erosion, increases in channel depth and diameter, and destruction of habitats such as gravel beds that are spawning or nesting grounds for fish, birds, crocodiles and other animals. A reduction in sediments reaching the coast can increase coastal erosion rates and reduce coastal protection.

Even when hydrological flows remain near natural conditions, increases or decreases in sediment supply can significantly impact channel size and river habitats, and thus river ecosystem health. Examples of this include the Phuthiatsana River in Lesotho, where the over-supply of sediment from a degraded catchment led a smothering of riffle and run habitats, infilling of pools and a decline in invertebrate and fish diversity (Southern Waters, 2006); and the Pangani Estuary in Tanzania, where a reduction of sediment supply as a result of hydropower dams led to excessive erosion of estuarine habitats through tidal action, reducing mangrove habitats, biodiversity, and

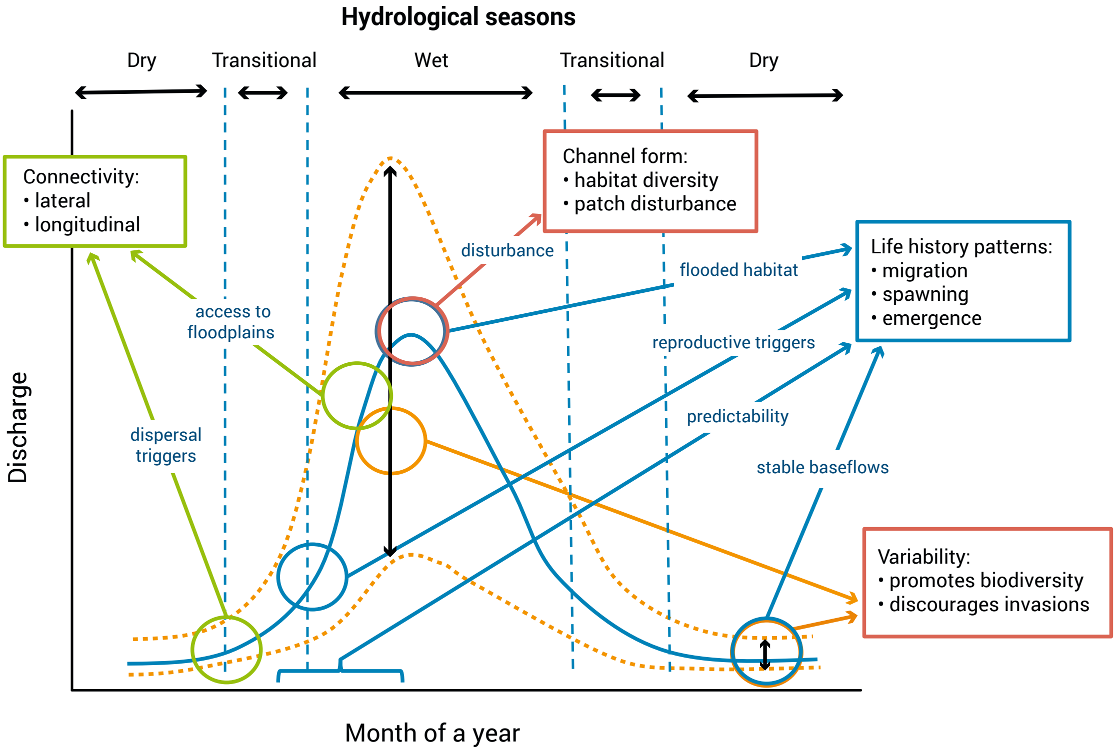


Figure 3. The importance of different parts of the hydrological flow regime (after Poff *et al.*, 1997; Bunn and Arthington, 2002).

severely affecting fish catch (PBWO/IUCN, 2007). Dams, impoundments and other in-channel obstructions (e.g. weirs, bridges, causeways, culverts, solid waste, stretches of river with no flow or poor water quality) block upstream and downstream passage of river, estuarine and marine organisms thus preventing the completion of their life-cycles and leading a loss of biodiversity and stability of the ecosystem and possibly impacting food production. The efficacy of fish passages intended to facilitate up- and downstream migration of fish past in-channel obstacles is a matter of considerable debate (Agostinho *et al.*, 2007; Dugan *et al.*, 2010; Nunn and Cowx, 2012), with the prevailing view that existing types and sizes of fish ladders have difficulty accommodating the full suite of structures needed to cater for the abundance and diversity of migrating fish and other organisms (such as prawns that have obligatory estuarine stages) and provide little or no assistance with downstream migration and larval drift (ICEM, 2010).

The quality of freshwater at any point in a river reflects the combined effects of many processes along the system (Peters and Meybeck, 2009). If surface waters were unaffected by human activities, most would have natural chemical concentrations suitable for an array of aquatic life and human uses. Land-based sources of pollution, most notably toxicants and nutrients, impede growth and reproduction in aquatic organisms, however, changing intra- and inter-species dynamics and feeding behaviours, disrupting overall ecological functioning and causing disease and mortality in a range of species (e.g. Scott and Sloman, 2004). Pollution impacts are exacerbated under conditions of low flow, whether these are natural or a result of abstractions and water resource developments, as lower flows decrease dilution and increase the residence time of pollutants in rivers and estuaries, thereby increasing the influence of degraded water quality on aquatic biota (Meybeck and Helmer, 1996). The most common approach to water quality protection is to place limits on the concentration of effluents and non-point source contaminants. These limits are only effective, however, if linked to the volume of water flowing in the river, because a specific concentration of effluents that would be adequately diluted during high flows could be very damaging to the river ecosystem during low flows (Chen *et al.*, 2013).

Estuarine, mangrove and marine ecosystems (see Plate 2) may be similarly affected, with the river alterations that are most likely to impact them being changes in the seasonal patterns of freshwater input (especially low flows and floods), changes in sediment loads and increased nutrient levels (Caddy and Bakun, 1995; Gillanders and Kingsford, 2002; Harris *et al.*, 2010). Changes in the low flows entering estuaries affect mouth state/ tidal exchanges and/or salinity regimes. Even small reductions in flow can result in hypersaline conditions if evaporation exceeds the combined inflow from river and sea. Hypersaline conditions above 45 parts per thousand (seawater is 35 ppt) are generally assumed to be toxic to estuarine life forms and negatively affect productivity levels (Whitfield, 1998). Significantly reduced freshwater flow through drought or human activities can also result in naturally-open estuaries closing, causing major changes to the nature of the estuary and the near-shore marine environment and affecting ecosystem services. Changes in the occurrence and duration of flood peaks linked to increased sediment loads could result in estuaries no longer flushing, mouths closing and reduced marine connectivity, with implications for fisheries.

Development-generated environmental disturbances are frequently aggravated by droughts (Binet *et al.*, 1995) and extreme floods, with ongoing human-induced pressures outside of these times reducing the ecosystem resilience. This can result in a ‘punctuated’ decline in the condition of the affected ecosystems.

2.3 Climate change and EFlows

It is predicted that climate change will affect the volume and timing of the flow of water, sediments, nutrients and biota that connect rivers, estuaries, coastlines and oceans (www.nationalgeographic.com/environment/global-warming/global-warming-effects/; IPCC, 2007) and, as such, could fundamentally influence the nature and condition of all aquatic ecosystems. This could be exacerbated by expected changes in ambient temperature, which would directly affect a wide range of essential life history stages in organisms, such as the fruiting and flowering of riparian plants (Reinecke *et al.*, 2014) and the emergence and migration of aquatic animals (Bunn and Arthington, 2002). Estuaries are additionally at risk from flooding as a result of sea-level rise (see Plate 2), which could completely change the shape and nature of an estuary and even its location, especially if these water-level changes coincide with major alterations in coastal geomorphometry and/or river water supply (Whitefield and Elliot, 2011). Ocean acidification (lowering of pH) also poses a risk to estuarine productivity, especially in systems that are already eutrophic as a result of nutrient pollution (Feely *et al.*, 2010).

Climate change scenarios, used to articulate the implications for aquatic ecosystems, can and should be incorporated into EFlows Assessments through rainfall run-off modelling, which indicates the probable change in the patterns of water and sediment delivery (Section 4.6).

2.4 Negotiating objectives for river and estuarine ecosystem status

Section 2.1 states that an EFlows regime for a river or estuary is chosen to support a level of health carefully selected by the society that interacts with the system. The EFlows Assesswment approach used in this process tends to be one of two kinds.

Prescriptive EFlows: A decision is already in place on the required ecological condition of a water body and a pattern of flows to support this is prescribed. This approach is useful where objectives are clear and the chance of conflict is small. It does not support the exploration of options.

Scenario-based EFlows: Where several options of management actions exist or levels of water conflict are high, scenarios can be used to predict the consequences. This approach reflects the fact that as soon as the natural flow of water, sediment or biota of a river or estuarine system is manipu-

Plate 2. Mangrove fringed esturary in Zanzibar, providing a natural barrier to sea-level rise.

lated, then as living dynamic ecosystems, they will start to change (Arthington, 2012). There ensues a shift in the balance between benefits gained by water resource developments and costs in terms of degrading ecosystems and ecosystem services. The EFlows Assessment helps decision makers and stakeholders understand this trade-off through scenarios of several possible levels of change (Figure 4), each describing such factors as, for instance, kilowatts of hydropower, hectares of irrigated crops, price of urban water (gains) and changes in fisheries, water quality and tourism (losses). This enables informed discussion on their preferred future and thus allows negotiation as per the requirements of IWRM[1].

2.5 An integrated river basin management approach

IWRM is "a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP-TAC, 2000). "It is a concept that promotes sustainable use of water, encouraging people to move away from traditional project-driven ways of operating and toward a larger-scale basin or regional approach that takes into account the overall distribution and scarcity of water resources and the

---

[1] IWRM is defined as a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

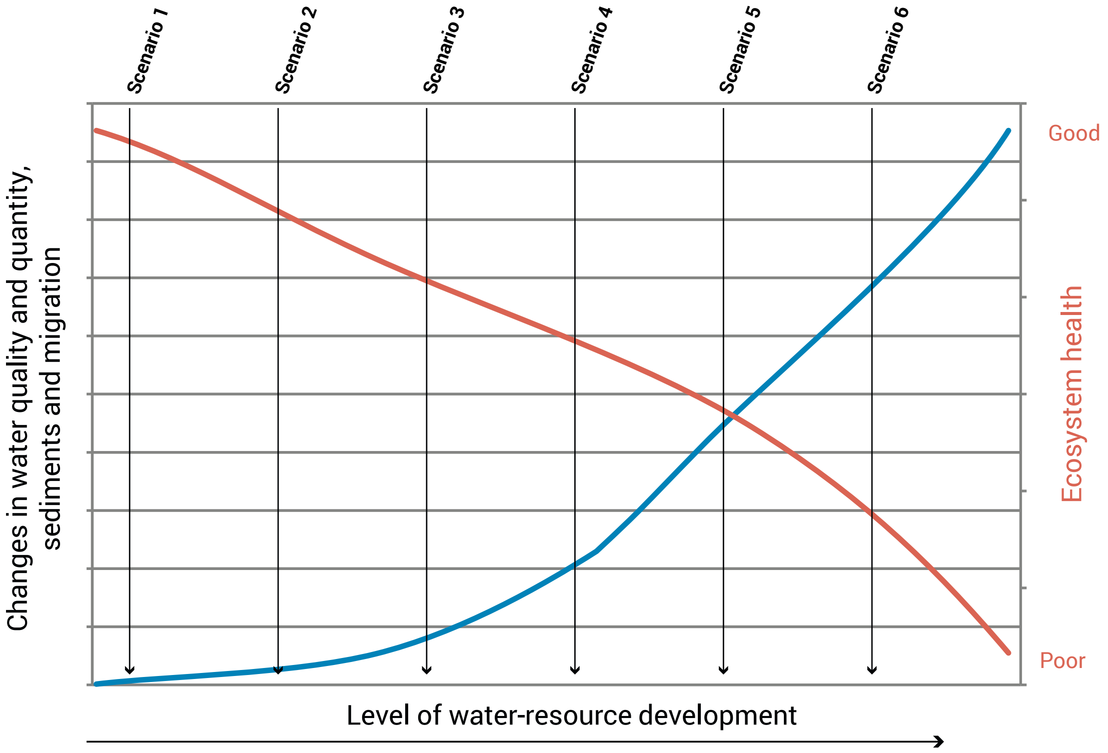


Figure 4. A scenario-based EFlows Assessment can provide detailed information on changes in ecosystem health (red axis) in response to changes in water quality and quantity, sediments and migration of biota (black axis) (King and Brown, 2009a; 2018) for any number of scenarios that reflect different levels of water-resource development or management options.

needs of other potential water users. In essence, IWRM is a political procedure that aims for sustainability of use; a process of balancing all water demands and supplies including those for environmental maintenance; an iterative approach that recognizes the need for adaptive management; and a way of life" (Halliday and Robins, 2007).

There is growing global recognition of the need for a basin-to-coast ecosystem management approach[2] to IWRM and EFlows (Dzwairo *et al.*, 2010) because the suite of links, dependencies, knock-on effects and feedback loops between and among aquatic ecosystems cannot be adequately addressed at smaller scales[3]. IWRM at the basin scale should include the near shore marine environment and comprise the following elements (Pegram *et al.*, 2013):

- consideration of trade-offs between economic, social and environmental objectives, and between existing and future demands;
- understanding of basin-scale interactions;
- a sophisticated approach to EFlows and genuine consideration of the importance of aquatic ecosystem functioning in providing life-supporting and enhancing services;
- a scenario-based analysis that addresses options, trade-offs and uncertainty in future development and climate; and
- prioritization to identify which of many demands are key for economic development, social justice and environmental protection.

The development of scenarios should be undertaken in the context of prevailing and possible resource management activities in a basin. Scenarios should consider expected variations in water quantity and quality, sediment supply and the movement of biota across the basin, but can also incorporate the evaluation of changes in resource use (e.g. in fishing effort or disturbance due to increased development) (Van Niekerk *et al.*, 2019) as well as other resource-economic or social issues.

---

[2] The term Integrated Coastal and River Basin Management being promoted by UNEP (http://www.gpa.unep.org) reflects this need.

[3] For instance, the EU's Water Framework Directive (EU 2000) and South Africa's catchment classification system (Dollar *et al.,* 2010).

3. EFlows Assessments

EFlows Assessments provide scientific information on the links between river flows and river/estuarine health and in their most comprehensive form predict basin-wide ecological and social outcomes linked to different water management options (King and Brown, 2018). As such, they can generate vital information on how river ecosystems function and what is needed in terms of water quantity, water quality and sediment regimes to support various levels of ecosystem services and the Sustainable Development Goals (SDGs; Figure 5).

3.1 EFlows Assessment methods

EFlows Assessment methods for rivers can be classified into five broad categories: hydrological, hydraulic, habitat rating, holistic (Tharme, 2003), and ecosystem-modelling (Overton *et al.*, 2014). In general terms, these represent a chronological progression over the last four to five decades in response to the increasing demand for sound scientific information on how rivers will respond to an array of human impacts. The general trend has been a move from:

- minimum flow recommendations to consideration of the regimes of water and sediments, and the movement of biota;
- little or no consideration of ecology, ecosystem services or social value to consideration of the functioning of the whole riverine/estuarine ecosystem and how ecosystems services and thus people could be affected;
- single-site assessments to whole basin assessments; and
- prescriptive to interactive/scenario-based assessments.

Figure 5. The hierarchy of Sustainable Development Goals (Image credit: Azote Images for Stockholm Resilience Centre).

A summary of the main changes in the nature of EFlows Assessments of rivers since the 1970s is shown in Figure 6 and Table 1. This shift is represented by a move from hydrological and hydraulic-rating methods to habitat simulation, holistic (predictive and scenario-based) and ecosystem-modelling methods. Apart from their more obvious differences in terms of time requirements, cost and suitability for application, these six categories also differ conceptually (Linnansaari *et al*., 2013) in the following ways:

- hydrological and hydraulic rating methods focus on the wetted area of the river and assume, usually without ecological proof, that a reduction in water availability will also reduce available habitat and/or impair ecosystem function;
- habitat simulation techniques focus on the wetted area of the river and suggest that there is an "optimum" flow that sustains their aquatic target species of choice (Jowett, 1997), cited in Linnansaari *et al*., 2013) without ecological proof that this sustains the whole ecosystem or social proof that this is optimum for society;
- holistic methods focus on the whole river ecosystem including banks, floodplains and non-aquatic species; they assume that ecosystems can be maintained at various levels of overall ecological health depending on the nature of the modified flow regime; and some incorporate socio-economic aspects; and
- ecosystem-modelling approaches seek to explain how ecosystems and their dependent people will respond to changes in a wide array of driving variables, including the quality, quantity and timing of the flow of water, sediments and biota (Plate 3).

It is also useful to recognize a 7th category (see Figure 6), termed here meta-analysis or extrapolation methods. These are methods that depend on

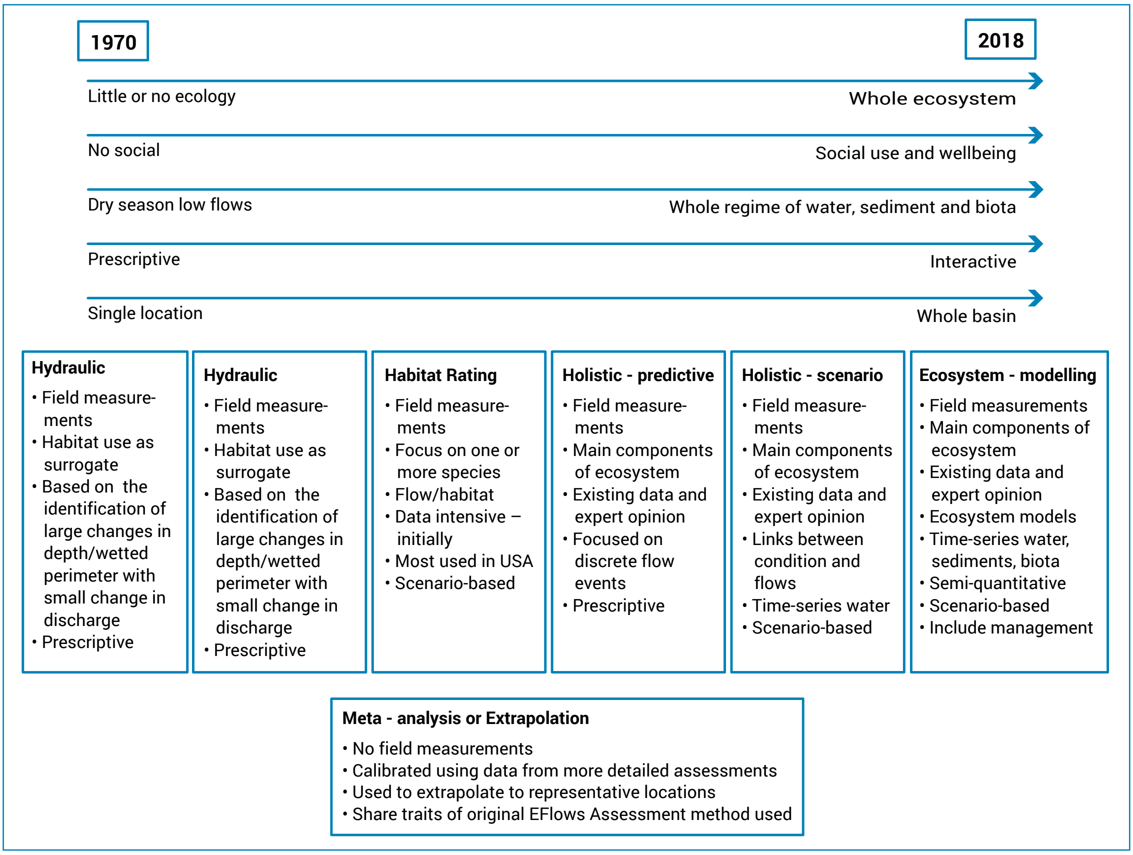


Figure 6. Changes in the nature of EFlows Assessments for rivers 1970-2018

detailed EFlows Assessments already completed for a river system. They derive simple rules or equations from the detailed assessment and use these through extrapolation to increase the number of sites for which scenarios can be produced, either in the same or in similar rivers. If they are based on basin-specific detailed EFlows Assessments and correctly calibrated, meta-analysis methods provide predictions of change at about the same quality as the original assessment, with the advantage that stakeholders can better understand the implications for their localities.

EFlows Assessments methods for estuaries followed similar trends to those for rivers, for similar reasons (Table 2). Early methods were hydrology-hydrodynamic methods (also called inflow methods (Adams, 2013)) that proposed a minimum river flow to the estuary to sustain estuarine functioning (van Niekerk *et al.*, 2019). These were followed by:

- condition methods, which selected physical conditions, such as salinity at a particular point, and described the river flows required to sustain these;
- resource-based methods, which focus on organisms of commercial importance for which inflows are determined to achieve a desired status; and
- ecosystem-based methods that develop relationships for a wide array of abiotic and biotic interactions and use these to predict responses to changes in freshwater inflow (Adams, 2013); van Niekerk *et al.*, 2019).

Table 1 and Table 2 indicate, for river and estuarine methods respectively, the input data required for some commonly-used EFlows methods: if a method is prescriptive or interactive/scenario-based; if it has included consideration of a range of ecosystem components, such as habitats, vegetation, biota; and if it has incorporated management considerations of resource use, such as over-fishing. The tables also indicate if the results are semi-quantitative and have included the social implications. The information provided by each of these types of methods is addressed in more detail in Section 3.3.

EFlows Assessments for marine environment are not common, although some countries, such as Australia, apply EFlows on a regional scale to protect selected fisheries resources (Halliday and Robins, 2007). In South Africa, the few that have been undertaken used the prescriptive assessment framework outlined in Table 3 (Van Ballegooyen *et al.*, 2007). These assessments have highlighted the importance of freshwater inflows in sustaining marine ecosystems and the urgent need for legislation that provides for EFlows for the nearshore marine environment.

Plate 3. Setting nets to sample river biota in the Ruhudji River, Tanzania.

Table 1. Commonly-used EFlows Assessment methods for rivers.

Method	Categorization	Prescriptive (P) or Scenario-driven (S)	Inputs					Integrated consideration of a full suite of impacts					
			Hydrology	Hydraulic	Sediments	Water Quality	Connectivity	Habitats	Vegetation	Biota	Management	Quantitative	Social uses
Q95	Hydrological	P	▨										
Wetted perimeter method[1]	Hydraulic rating	P	▨	▨									
Instream Flow Incremental Methodology (IFIM)[2]	Habitat simulation	S	▨	▨		▨	▨	▨		▨		▨	
Computer Aided Simulation Model for Instream Flow and Riparia (CASiMiR)[3]	Habitat simulation	S	▨	▨						▨		▨	
System for Environmental Flow Analysis (SEFA)[4]	Habitat simulation	S	▨	▨						▨			
The Building Block Methodology (BBM)[5]	Holistic	P	▨	▨		▨		▨	▨	▨			
Eco Modeller[6]	Ecosystem-modelling	P	▨	▨	▨	▨	▨	▨	▨	▨			
Habitat-Flow-Stressor-Response (HFSR)[7]	Holistic	P	▨	▨				▨	▨	▨			
Hydrologic Engineering Center-Ecosystem Functions Model (HEC-EFM)	Ecosystem-modelling	S	▨	▨		▨	▨	▨	▨	▨			
Downstream Response to Imposed Flow Transformation (DRIFT)[8]	Ecosystem-modelling	S	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Murray-Darling Basin Plan SDL Adjustment Ecological Elements[9]	Ecosystem-modelling	S	▨	▨		▨	▨	▨	▨	▨	▨	▨	
The Tennant Method[10]	Meta-analysis/hydrological	P	▨										
The Desktop Model[11]	Meta-analysis /holistic	P	▨										
ELOHA[12]	Meta-analysis /holistic	P	▨										
DRIFT EFlows Algorithms[13]	Meta-analysis/ecosystem	S	▨		▨							▨	

Sources: 1. Gippel and Stewardson (1998); 2. Stalnaker et al. (1995); 3. Jorde (1999); 4. www.sefa.co.nz; 5. King and Louw (1998); 6. http://ewater.org.au/products/ewater-toolkit/eco-tools/; 7. O'Keeffe et al. (2002); Hughes and Louw (2010); 8. Brown et al. (2013); 9. Overton et al. (2014); 10. Tennant (1976); 11. Hughes and Hannart (2003); 12. Poff et al. (2010); 13. Southern Waters (2019a).

Table 2. Commonly-used EFlows Assessment methods for estuaries (Adams, 2013; van Niekerk *et al.*, 2019).

Method	Categorization	Prescriptive (P) or Scenario-driven (S)	Inputs					Integrated consideration of a full suite of impacts					
			Hydrology	Hydrodynamic (+ salinity)	Water Quality	Sediments	Connectivity	Habitats	Vegetation	Biota	Management	Quantitative	Social uses
Percentage of Flow Method[1]	Hydrological / hydrodynamic	P	▨	▨	▨			▨	▨	▨			
Water Withdrawal Regulation Method[2]	Hydrological	P	▨	▨	▨	▨		▨	▨	▨			▨
X^2 Isohaline Position Method[3]	Hydrodynamic	P	▨	▨						▨			
Texas Estuarine Mathematical Programming model (TxEMP)[4]	Resource-based	P	▨	▨	▨					▨			
Texas Freshwater Inflow Method	Resource-based	P	▨	▨						▨			
National River Health Program[5]	Holistic	S	▨	▨	▨	▨	▨	▨	▨	▨	▨		
Valued Ecosystem Component (VEC) Method[6]	Resource-based	P	▨	▨		▨		▨	▨	▨			
Flow for Fisheries Method[7] (applied nearshore marine)	Resource-based	P	▨	▨						▨			▨
Estuary environmental flows assessment methodology (EEFAM)[8]	Holistic	P	▨	▨		▨	▨	▨	▨	▨	▨		▨
RSA Estuary EWR Intermediate / Comprehensive[9]	Ecosystem-modelling	S	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Downstream Response to Imposed Flow Transformation (DRIFT)[10]	Ecosystem-modelling	S	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Water Withdrawal Regulation Method	Meta-analysis /hydrological	P	▨	▨	▨	▨		▨	▨	▨			
X^2 Isohaline Position Method	Meta-analysis /holistic	P	▨	▨						▨			
RSA Estuary EWR Desktop[11]	Meta-analysis / ecosystem	S	▨	▨	▨	▨	▨	▨	▨	▨	▨		
Texas Freshwater Inflow Method	Meta-analysis / ecosystem	P	▨	▨						▨			

Sources: 1. Flannery *et al.* (2002); 2. Alber and Flory (2002); 3. Jassby *et al.* (1995); 4. Montagna *et al.* (2009); 5. Peirson *et al.* (2002); 6. Alber (2002), Doering *et al.* (2002), Mattson (2002); 7. Halliday and Robins (2007); 8. Lloyd *et al.* (2012); 9. Van Niekerk *et al.* (2019); Adams et al. (2002); 10. Clark and Turpie (2014); 11. Van Niekerk *et al.* (2019).

3.2 Trends in EFlows Assessments in the WIO region

EFlows Assessments in the WIO region began in the early 1990s, and by the end of 2018 over 200 EFlows Assessments had been completed for rivers or estuaries[4]. The bulk of these were in South Africa, but several assessments have also been undertaken for rivers and estuaries in Kenya, Mozambique and Tanzania (Figure 3.3; Plate 4) (Brown *et al*., 2020). No assessments were located for the island nations of Comoros, Madagascar, Mauritius, Reunion or Seychelles, or for Somalia.

Trends in EFlows Assessments in the WIO region indicate that:

- The use of more detailed (holistic and ecosystem) EFlows Assessments tends to predate that of rapid (hydrological) assessments (Figure 3.5), with the latter tending to be generalized and covering a wider geographical area. In other words, initial in-depth EFlows Assessments generated findings that were then used to develop indices for use in rapid methods and to increase the spatial spread.
- There is a progressive move away from the use of prescriptive methods towards methods that allow some form of scenario analysis and negotiation of trade-offs.
- There is a progressive move towards basin-wide assessments, as encapsulated by the Inkomati (AfriDev, 2000; Godfrey, 2002), Maputo (Louw, 2007; Louw and Koekemoer, 2007; Paterson *et al*., 2008), Pangani (PBWO/IUCN, 2009), Umbeluzi (SWECO, 2005), Rufiji (McClain *et al*., 2016; O'Keeffe, 2017), Wami (Coastal Resource Centre, 2008; GLOWS-FIU, 2014), Mara (LVBC and WWF-ESARPO, 2010) and Msimbazi basin-wide EFlows Assessments and the classification processes underway in South Africa and Tanzania.

Table 3. Actions required for including the nearshore marine environment into an EFlows Assessments (Van Ballegooyen *et al*., 2007).

STEP	ACTIONS
Step 1: Define ecosystem extent and resource units	• Define legislative obligations (e.g. biodiversity protection, sustainable fisheries, coastal protection - beach development) • Identify ecosystem extent (delineation) • Identify key ecosystem functions and services • Identify ecosystem resource use
Step 2: Identify assessment targets	• Identify biodiversity and resource use targets (e.g. fish nurseries, fisheries production, Marine Protected Areas, sediment requirement of beaches).
Step 3: Determine sensitivity to river flow	• Determine ecosystem sensitivity to flow • Identify relevant abiotic components (e.g. habitat) and assess responses to flow modification • Describe the implications of baseline river flow regimes on selected biological components (i.e. keystone/indicator species life-cycle and habitat requirements in terms of flow)
Step 4: Assess EFlows	• Assess scenarios • Predict the responses, if any, to predicted change in abiotic drivers • Describe the implications of river flow alteration on selected biological components • Evaluate socio-economic implications • Recommend EFlows parameters (e.g. freshwater flow, river water quality and sediment delivery)
Step 5: Set monitoring targets	• Set monitoring targets for nearshore marine environment

---

[4] These data are a result of a web-based search, and it is acknowledged that information presented is incomplete. Some studies do not appear on web sites, and in other cases only the final decision on EFlows is available in public documents with nothing documenting how this was reached. In South Africa, for instance, hundreds of one-off EFlows assessments using the Desktop Model (Hughes and Hannart 2003; Hughes and Louw 2010) have been conducted as part of Water Use License (WUL) applications, but are not recorded here because, typically, they were tick-box exercises for the WUL. Some of these assessments were upgraded in later detailed EFlows assessments. It is possible that work in other WIO countries has been similarly under-reported and is thus not available for analysis here.

- General recognition that confidence in the results of EFlows is dependent on the quality of the primary input - the hydrological and hydraulic/hydrodynamic data.

It is important to note that the numbers included in Figures 7 and 8 are for the EFlows Assessments completed rather than the number of sites and/or area assessed in each, which depends on the method used. This is relevant because, for instance, meta-analysis assessments tend to cover greater areas at low confidence than holistic or ecosystem-modelling assessments, which cover smaller areas at higher confidence (see Section 4.2).

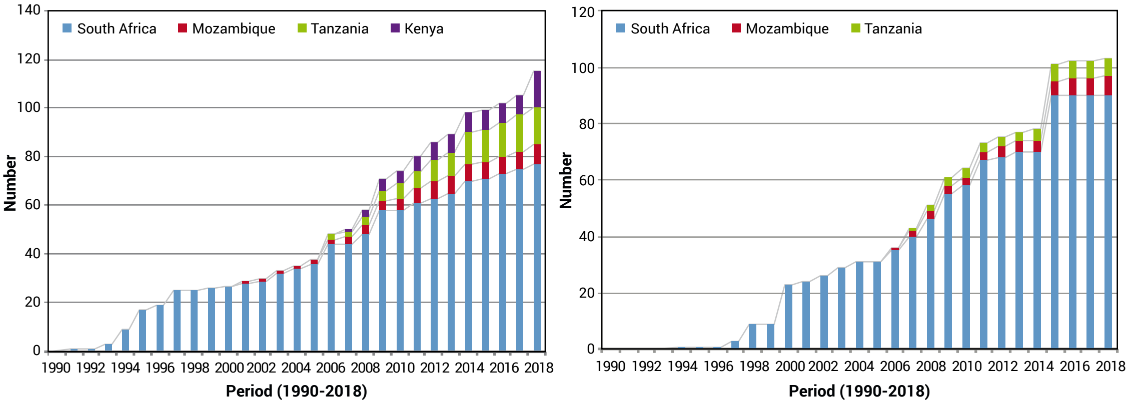


Figure 7. Cumulative number of EFlows Assessments for rivers (left) and estuaries (right) in WIO countries: 1990 2018.

Plate 4. Measuring depths and velocities associated with microhabitat as part of EFlows training exercises in the Ruvu River, Tanzania in 2003.

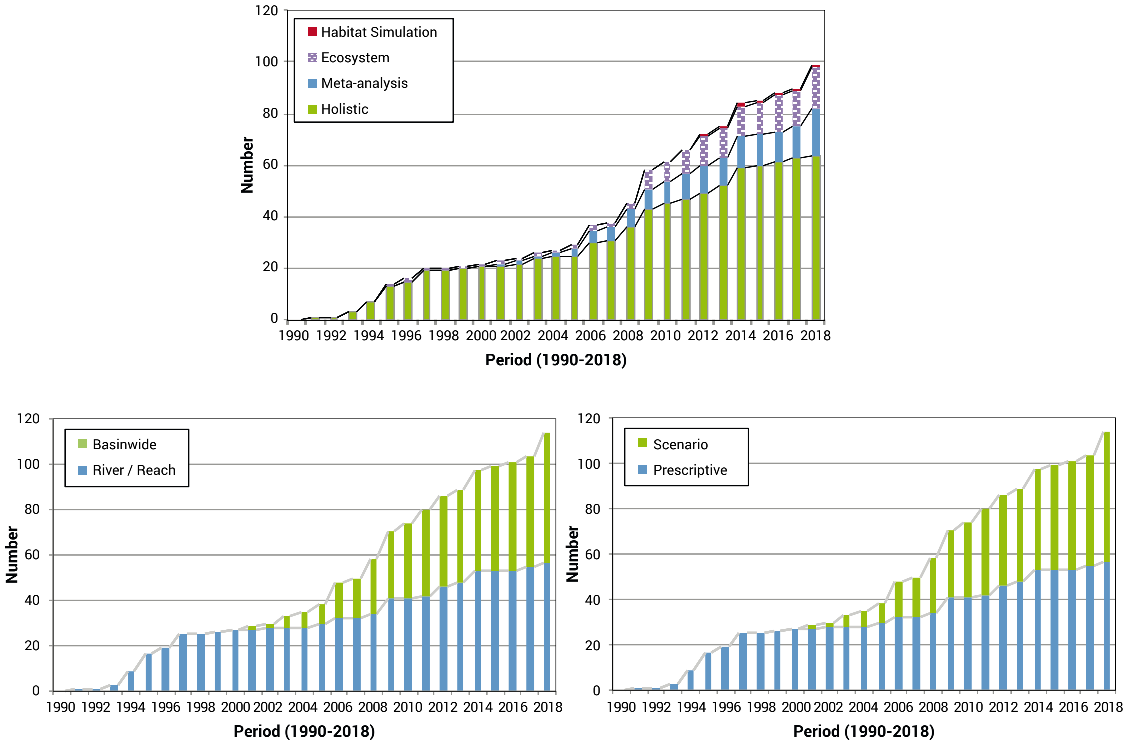


Figure 8. Method category (top), approach (bottom left) and spatial focus (bottom right) of river EFlows Assessments in WOI region: 1990-2018.

EFlows for the marine environment have only been conducted offshore of the Thukela River (hydrology-biotic correlation study) (Demetriades *et al.*, 2000) and the Orange River (hydrodynamic and sediment coupling to biotic responses) (Van Niekerk and Lamberth, 2013).

3.3 Overview of information provided by EFlows Assessments

The information provided by an EFlows Assessment, and thus its usefulness for other assessments decision-making or management depends heavily on the method used and the amount, nature and scope of relevant data available (Section 5).

Simplistic hydrological (e.g. Q95; Percentage of Flow) or hydraulic rating (e.g. Wetted Perimeter) methods were the first attempt from an engineering base to provide information on flows for maintaining river ecosystems. They have low data requirements, only addressing the physical aspects mentioned in their titles, and generally provide simplistic answers that have little or no ecological relevance. They offer very little justification or insight into how their recommended flows are derived or what they are expected to achieve. As the science and understanding of river basins has evolved and matured, these older methods have received considerable scrutiny because of the lack of scientific evidence they present to support their traditional claims that aquatic ecosystems can be sustainably managed through the provision of a ‘minimum flow’. A significant body of scientific evidence now exists that indicates that in fact aspects of the full flow regime are required for sustaining river ecosystems (King and Brown, 2018). The general consensus among EFlows practitioners is that ‘methods’ such as the Q95 or the 10% rule are not appropriate options for any level of EFlows Assessment and should be avoided.

Modern EFlows Assessment methods address the complexity of aquatic ecosystems and their

Table 4. Definitions of the ecological condition categories (after Kleynhans, 1996).

CATEGORY	DESCRIPTION
A	Unmodified. In a natural condition.
B	Near natural. A small change in natural habitats and biota has taken place but the ecosystem functions are essentially unchanged.
C	Moderately modified. Loss and change of natural habitat and biota has occurred, but the basic ecosystem functions are still predominantly unchanged.
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E/F	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.

responses to development. They allow a more genuine consideration of a broader suite of possible impacts, such as pollution and resource utilization, and increase the chances of supporting sustainable use. They should be transparent and provide the reasoning behind the assessment, and in so doing promote greater understanding of river and estuarine ecosystems.

Most prescriptive holistic methods (e.g. BBM, listed in Table 1) will provide a rudimentary annual flow regime without consideration of events with a return period of 1 to 2 years or more. Their outputs comprise discharge requirements for low flows and intra-annual (within year) floods that are expected to support the maintenance of the river or estuary in a pre-stated ecological condition, which is usually expressed on a scale of near natural (A) to seriously modified (E/F) (Table 4). They usually provide motivations as to what each discharge is expected to achieve. These methods tend to be computationally simpler than the scenario methods and have proved useful when the desired condition for a river or estuary ecosystem is pre-agreed. They are, however, limited with respect to evaluating changes to the flow regime, such as those linked to different dam designs or operating rules, and are not useful for climate change predictions.

Scenario-based holistic methods (e.g. HFSR), habitat simulation methods (e.g. IFIM) or resource-based methods (e.g. Texas Method) all evaluate the effects on aquatic ecosystems of changes to their flow regimes. They tend to focus on target species, such as those deemed to have commercial value. They do not consider flood events with a return period of ≥1 to 2 years, changes in sediment supply, or longitudinal and lateral connectivity of the ecosystem.

Ecosystem approaches (e.g. DRIFT; HEC-EFM) may have a custom-built ecosystem model for the aquatic system under consideration and provide more in-depth predictions of change. The DRIFT ecosystem model for the Okavango Basin, for instance, predicts the outcome for 70 biophysical indicators and eight social indicators at eight sites distributed across the whole system (King *et al.*, 2014). Such approaches may also address changes in sediment supply; the implications of barriers (such as dams) to biotic movement (connectivity); and be able to consider other aspects such as mitigation measures, restoration, or management interventions such as regulations for fishing and sand mining.

There is a strong link between ecosystem condition and ecosystem services, and so most EFlows Assessment methods predict or imply to some extent the social implications of selecting one condition over another. Some EFlows Assessment methods that yield semi-quantitative estimates of change in habitats or species (Table 1; Table 5) can take predictions a step further by computing in detail the social implications of changes in ecosystem services. Typical indicators used to predict the social impacts could include household incomes, potable water, livestock health and public health (water-borne diseases).

In some cases, these computations are carried out using separate models while others offer the option of integrating the social assessment into the EFlows Assessment model.

3.3.1 EFlows information to support the sustainability of marine ecosystems

The mean annual discharge of freshwater from rivers into the WIO is in the region of 40x103 m^3s^{-1} (Dai and Trenberth, 2002) together with hundreds of millions of tonnes of sediment (Mouyen *et al.*, 2018), associated detritus and nutrients. The volume and seasonality of the combined freshwater and sediment discharges drive the morphodynamics and biodiversity of coastline habitats, such as beaches, and shallow sub-tidal habitats, with examples including the Tugela Banks off the Thukela River (DWAF, 2004) and the Sofala Banks off the Zambezi River. They also provide cues for spawning and migration (Quiñores and Montes, 2001; Demetriades *et al.*, 2000) and influence the availability of estuarine nursery habitats for a range of organisms (e.g. Box 1). The associated lower salinities and elevated nutrients stimulate phytoplankton (Carter and Schleyer, 1998; Smetacek, 1986), zooplankton productivity and other food web processes, as well as detritus is an important source of food for, inter alia, microorganisms (Berry *et al.*, 1979; Schleyer, 1981; Berry and Schleyer, 1983; Whitfield, 1998), red bait, mussels, oysters (Porter, 2009; Mann and Lazier, 2013), prawns (e.g. Box 1) (Mann and Lazier, 2013; Gammelsrød, 1992) and fish (Lamberth *et al.*, 2009).

Changes in water quality, the flow of water and sediments, and system connectivity can have significant consequences for marine biodiversity and productivity, with knock-on effects to people. It is thus imperative that EFlows for rivers and estuaries, the outputs of which are intended to support the sustainability of marine ecosystems, address the dynamics of water quality and the flow of water, sediments and biota from rivers into estuaries and into the marine environment.

Box 1. Effects of freshwater and sediments on marine prawn populations
(from Paterson *et al.*, 2008)

Most WIO prawn species inhabit shallow inshore waters as adults. These prawns copulate and spawn at sea and the eggs hatch into pelagic larvae, which develop through a number of larval stages. The final stage is a benthic post-larval prawn that requires a nursery area that offers relative safety and abundant food, such as an estuary or sheltered bay. After approximately three months in the nursery area, the juveniles move back into the marine environment. Thus, the timing and volume of freshwater and sediment affects:

- the amount of river/estuarine detritus (Monteiro and Matthews, 2003); Whitfield, 1998) and phytoplankton production (Monteiro and Marchand, 2007; Carter and Schleyer, 1998), which provide food for adults and larvae
- the suitability of estuarine habitats as nursery areas (Whitfield, 1998)
- the quality and availability of sub-tidal habitats for adults (Van Ballegooyen *et al.*, 2007)
- cue for migration between estuaries and the nearshore environment (Vance *et al.*, 1998; Staples and Vance, 1986).

Note: many species of freshwater prawns, *Macrobrachium* sp., spawn in the brackish water found in estuaries and migrate upstream to grow to adulthood.

Table 5. Strengths and weakness of categories of EFlows Assessment methods.

METHOD	STRENGTHS	WEAKNESSES
Hydrological (10% rule)	• Simple and quick • No need for river scientists • Allows an 'upfront' proportion of flow to be allocated 'to environment' in hydrological models	• Inconsistent • No basis in science • Used without understanding the implications • Often do more harm than good
Habitat simulation	• Derives quantitative relationships between target species and hydraulic conditions • Useful in negotiating water allocations for rivers • Helps trigger development of holistic methods	• Focuses on hydraulic habitat without recognition of the influences of other environmental stressors on species, such as changes in the timing of flows or changes in sediments or water quality • Focuses on aquatic species to the detriment of riparian species and on lower flows but not floods • Focuses on single species
Holistic	• Provides extensive and detailed manual for use • Simple concept to grasp and work with • Some methods (e.g. BBM) have user manuals with written guidelines for data collection and analysis • Acts as a stepping stone for more complex interactive methods	• Requires expert input • Due to the prescriptive nature, outputs can't be negotiated • Various questions raised by stakeholders when they felt that a more broad-based process should be employed • Impacts of flow changes on subsistence users not adequately addressed • Impacts of changes in timing of flows not addressed • Sediment not addressed • Does not address flows higher than average annual ones and so cannot be used to assess e.g. climate change, extreme events • Consequences of not meeting EFlows not provided • Cannot react to scenarios
Ecosystem modelling	• Provides semi-quantitative or quantitative predictions of change for use in planning, design and operation of water resources infrastructure • Can import time-series from hydrological, sediment, water quality or biological modelling where they exist and use these in EFlows Assessment • Some methods (e.g. DRIFT and EcoModdeller) have software with user manuals with written guidelines for data collection and analysis and are well documented in international literature • Strong links to social and resource economics • Provides the information needed for monitoring programmes and adaptive management strategies • Can consider hydrological and other data at any time-interval (monthly, daily or hourly) • Models created for an EFlows Assessment are available for subsequent use	• Complex • Requires an understanding of the functioning of the ecosystems and of the model • Requires expert input
Meta-analysis	• Simple and quick, not much expertise required • Expert input not required • Can play a role in rapid, low-resolution assessments, with proper understanding of limitations • Can be used to extrapolate data from more detailed EFlows Assessments over a wider spatial scale or to increase spatial resolution	• Can only be used after they have been locally calibrated through more detailed EFlows Assessments • Flows require adjustments for wet and dry years • Does not address flows higher than annual ones • Consequences of not meeting EFlows or operating not provided

4. Undertaking an EFlows Assessment

Different methods require different procedures but the following section outlines an overall suite of considerations and actions, thus providing some insight into the nature of the more complex assessments. Rapid methods may or may not include a limited version of some of these steps. The following process should be headed by an experienced EFlows practitioner (Box 2).

4.1 Nature of the assessment, budget, method and team

A preliminary set of activities addresses the nature and budget of the assessment.

4.1.1 Purpose and scope

In general, EFlows methods are employed to advise on the ecological and social outcomes of sustainable development or restoration projects. Within the WIO, the overall objective of EFlows Assessments for rivers and estuaries is to support the sustainability of marine ecosystems, with further definition of objectives emerging depending on the challenges presented by individual riverine and estuarine systems.

4.1.2 Budget

The cost of an EFlows Assessment depends on such factors as the method used, the number of sites, the range of ecosystems and social aspects covered, the composition of the EFlows Assessment team and the level of capacity-building undertaken. In general, complex methods cost more than simple, rapid rule-of-thumb methods, and specialist teams cost more than one or a few more generalized practitioners. If the results are to be used in high-conflict situations, to make decisions on sensitive ecosystems, or to adhere to the

Box 2. The role of the EFlows Practitioner in an EFlows Assessment

EFlows Assessments, particularly those using holistic or ecosystem-modelling methods, can be complex. Leading such an assessment requires suitable qualifications, an understanding of the functioning of the ecosystem under consideration, a thorough understanding of EFlows Assessments and the methods available for undertaking them, and experience in managing large multi-disciplinary teams of scientists and other professionals. Responsibilities of an EFlows Practitioner include:

- Overall responsibility for the successful execution of the project
- Advising the government, client, developers and/or funders on meeting project objectives and deliverables
- Team selection and personnel management, including Terms of Reference and budgets for specialists, and planning activities and steering of the EFlows Assessment team
- Facilitating procurement of long-term data sets, in particular hydrology
- Motivating and facilitating the selection of scenarios for analysis
- Project direction, including obtaining team and stakeholders inputs on site, method and indicator selection
- Consideration and integration of cross-cutting themes
- Assisting with the development of evaluation criteria to assess the scenarios
- Financial planning and controlling use of project funds, including invoicing, record keeping and reporting
- Capacity building within the EFlows project team and stakeholders, including design and implementation of training courses
- Quality control of all products, including review of the specialist's reports
- Stakeholder engagement
- Report writing
- Presenting progress and final outputs.

principles of IWRM, a holistic or ecosystem-modelling approach with a specialist team should be attempted (see Table 1 and Table 2).

Most detailed EFlows Assessments take 12 to 24 months to complete, although work will not be continuous over that time. This time span allows data to be collected over at least one annual hydrological cycle, starting in the dry season when the features of the river channel can be seen and measured (Brown *et al.*, 2020). Rapid methods can take a few days or weeks, with outputs concomitant with the low investment.

Table 6 and Table 7 provide estimates of the time allocated to personnel for the technical aspects of an EFlows Assessment using a holistic or ecosystem approach for rivers and estuaries, respectively. The estimate for rivers assumes ten representative locations distributed throughout a

Table 6. Personnel time (days) for different resolution levels of flow assessments per river, excluding travel and stakeholder liaison time, and disbursements. These are estimates only.

METHOD	UNITS	HOLISTIC OR ECOSYSTEM APPROACH		EXTRAPOLATION USING META-ANALYSIS METHOD [a; b]
LEVEL OF RESOLUTION OF ASSESSMENT		MEDIUM RESOLUTION	HIGH RESOLUTION	
Team and effort				
No. of EFlows practitioners	People	1-2	1-2	1
No. of discipline specialists	People	4-6	6-10	-
No. of site visits	Trips	1-2	2-3	0-1*
No. of scenarios	Number	3-4	4+	1-2
Overall time estimates				
Preparation	Person days	20-30	40-60	1-2
Data collection[c]	Person days	60-80	80-160	2-10
Assessment	Person days	60-80	80-160	2-10
Write-up	Person days	20-30	40-60	2-4
Total	Person days	160-220	240-440	7-16
Total time span of assessment	Person months	6-12 months	12-24 months	2-6 weeks
Extras				
Flow routing for peaking[d]	Person days	10-20	15-30	n/a
Restoration and offset measures	Person days	10-20	20-60	n/a
Social aspects	Person days	40-60	60-80	n/a
Additional specialist	Person days	30-40	40-50	n/a
Additional scenario	Person days	2-10	4	n/a

a: 20 additional locations
b: Excluding collation and preparation of hydrology
c: Excluding travel time
d: For one hydropower plant

* It is best for an EFlows Practitioner to visit the study area, even for a desktop assessment, as insights gained on the ground are invaluable when making decisions related to applying the EFlows Assessment method

Table 7. Personnel time (days) for different resolution levels of flow assessments per estuary, excluding travel and stakeholder liaison time, and disbursements. These are estimates only.

METHOD LEVEL OF RESOLUTION OF ASSESSMENT	UNITS	HOLISTIC OR ECOSYSTEM APPROACH[a] MEDIUM RESOLUTION	 HIGH RESOLUTION
Team and effort			
No. of EFlows practitioners	People	1	1-2
No. of specialists	People	4-6	6-10
No. of site visits	Trips	1-2	2-4
No. of scenarios	Number	3-6	4+
Time estimates			
Preparation	Person days	10-20	20-40
Data collection[b]	Person days	20-40	80-160
Assessment	Person days	60-80	80-120
Write-up	Person days	15-20	20-40
Total	Person days	105-160	200-360
Total time span of assessment	Person months	6-12 months	12-24 months

a: Excluding collation and preparation of hydrology
b: Excluding travel time

basin, readily available daily hydrological data (i.e. discharge for selected locations), and a dry season start to the project.

Factors that significantly increase effort, such as updating or generating hydrological data through rainfall runoff modelling, locations that require more complex hydraulic/hydrodynamic modelling (e.g. extensive floodplains and/or complex estuaries), the location of water-resource developments and the extent of stakeholder liaison are excluded because they vary widely between locations, basins and projects and are impossible to generalize. Table 6 also includes time estimates for extrapolation of the data generated by the more detailed EFlows Assessment to additional locations within the same river basin.

4.2 Select an appropriate EFlows Assessment method

An appropriate method for any situation is dictated by, inter alia, the degree of potential conflict or conservation importance of the river or estuarine system, the type and scale of management and water-resource developments to be considered, the detail of output hoped for, the available funds and the objective to be achieved. Table 8 lists the attributes of commonly used methods, which can help clarify thinking on what is possible with the data and funds available and the hoped-for outcomes. The following explanatory notes apply:

- Ecosystem type: Many methods are specific to a particular ecosystem type, e.g. river or estuary. If the scope of the EFlows Assessment encompasses a variety of different aquatic ecosystems, it is often best to select different methods for each ecosystem type and to harmonize their outputs. Alternatively, some methods are suitable for use across a wider array of ecosystem types.
- Calibration: Meta-analysis methods should not be applied in regions for which they have not been calibrated. They are, however, extremely valuable for a particular ecosystem when based on the outcomes of a

Table 8. Decision matrix for selection of a suitable EFlows Assessment method.

CATEGORY		**HYDRO-LOGICAL**		**HOLISTIC**			**ECOSYS-TEM**		**META-ANALYSIS**			
Examples of methods **Criteria**		**Tennant Method**	**Percentage of Flow**	**BBM**	**HFSR**	**RSA Estuary I/C**	**Eco-modeller**	**DRIFT**	**Desktop Method**	**ELOHA**	**DRIFT equations**	**RSA Estuary DT**
Suitability for use												
Ecosystem type	EFlows for rivers			■	■		■	■	■	■	■	
	EFlows for wetlands, floodplains, lakes			■			■	■			■	
	EFlows for estuaries		■			■	■	■				■
Calibration	Provides data that can be used to extrapolate to other locations			■	■	■	■	■				
	Receives data that can be used for extrapolation								■	■	■	■
Minimum data requirements	Monthly hydrological data	■	■		■	■			■	■		■
	Daily hydrological data			■			■	■			■	
	Hydrodynamic modelling					■						
	Water quality (nutrients and salinity)					■						■
Prescriptive												
Information provided	Can be used at a desktop-level to provide coarse-level information over large areas	■							■	■		■
	Minimum dry season water flows to support ecosystem in a range of conditions	■	■	■	■	■	■	■	■	■	■	■
	Monthly volumes of water to support ecosystem in a range of conditions	■	■	■	■	■	■	■	■	■	■	■
	Relative abundance of specific habitats/species linked to a range of ecosystem conditions							■			■	
	Range for other parameters, e.g. WQ and sediments, to support ecosystem in a range of conditions							■			■	

CATEGORY		**HYDRO-LOGICAL**		**HOLISTIC**			**ECOSYS-TEM**		**META-ANALYSIS**			
Examples of methods		**Tennant Method**	**Percentage of Flow**	**BBM**	**HFSR**	**RSA Estuary I/C**	**Eco-modeller**	**DRIFT**	**Desktop Method**	**ELOHA**	**DRIFT equations**	**RSA Estuary DT**
Criteria												
Scenario-based												
Information provided	Implication for ecosystem condition for scenarios that include effects on water discharge in specific seasons				▨	▨	▨	▨	▨	▨	▨	▨
	Implications for ecosystem condition for scenarios that include effects on timing of flows, i.e. onset/duration					▨	▨	▨			▨	
	Implication for ecosystem condition for scenarios that include hydrological events > 1 year return period					▨	▨	▨				
	Implication for ecosystem condition for scenarios that include within-day flow variations, e.g. hydropeaking						▨	▨				
	Implication for ecosystem condition for scenarios that include water quality					▨	▨	▨			▨	▨
	Implication for ecosystem condition for scenarios that include volume and timing of sediment supply					▨	▨	▨			▨	▨
	Implication for ecosystem condition for scenarios that include barriers to migration of biota					▨	▨	▨				
	Implication for ecosystem condition of revitalization to address water quality, buffer zone, harvesting, etc.						▨	▨				
	Semi-quantitative change in specific habitats/species for the above				▨	▨	▨	▨			▨	▨

detailed EFlows Assessment for that same system.

- Minimum data requirements: The absolute minimum data requirements without which the method cannot be applied.
- Prescriptive or scenario-based (see Section 2.4.)
- Information provided: While the availability and timing of water is a driving factor in river or estuarine condition, it is not the only factor. The more rapid methods might exclude one or more other drivers of ecosystem conditions, such as water quality, sediments or connectivity, and may assume that these will not vary from baseline condition or that it does not matter if they do. If such factors are seen as likely major influences of the ecosystem, the method chosen should be one that includes them. Methods with transparent relationships and user-friendly outputs can be understood by a wide range of people in negotiations.

There are disadvantages to stipulating one particular method across a wide geopolitical area such as the WIO region, as this has a tendency to stifle progress, competition and innovation. There are, however, advantages to harmonising EFlows methods across the region by establishing a standard set of criteria and minimum output format. These advantages include:

- routine data collection for hydrology and sediments can be tailored to particular methods;
- river and estuarine specialists become familiar with data requirements and inputs to the EFlows Assessment;
- stakeholders become more familiar with outputs and interpretation of EFlows Assessment data; and
- some methods, e.g. HFSR and DRIFT generate method specific databases that can be added to and updated over time and adapted for use in other locations.

It is often difficult, expensive, time-consuming, and possibly unnecessary, to do detailed EFlows Assessments for every river reach and every aquatic ecosystem in a basin. Information generated at a small number of locations (see Plate 5), can be extrapolated using a meta-analysis method (Section 3.1) to a large number of locations through the basin in order to inform a basin-wide decision-making or management process (Box 3). Planning for the extrapolation at the outset of a study, in particular the careful selection of representative sites/locations, maximizes the usefulness of the information generated by the detailed EFlows Assessments for extrapolation. Using regional experts facilitates the extrapolation process, as local expert knowledge can be as important as historical data in a data-limited environment.

4.2.1 Supporting models

Depending on the method chosen and the objectives, a range of supporting models may be needed to provide important input. Common examples of such models include:

- Rainfall/runoff models, which in the absence of measured flow data can be used to generate hydrological time-series.
- Water-resource models, which provide the impacts of development on the hydrological regime. These are the basis of all EFlows Assessment methods.
- Ecohydraulic/hydrodynamic models, which translate hydrological data into conditions experienced by people/biota (water depths, velocities, extent of inundation, etc.).
- Sediment models, which reflect sediment sources and sinks and predict the outcomes of, for instance, inserting a dam as a barrier to sediment movement.
- Water quality models, which describe present conditions and predict changes linked to proposed interventions.

The models above focus on the EFlows Assessment, which will provide information on ecosystem responses to changes as a result of developments or management interventions. A different suite of models is needed to provide the implications of the different scenarios for developments, economics and/or policy implementation.

4.2.2 Consideration for the selection of methods for WIO EFlows Assessments

Where possible, WIO EFlows Assessments should consider the following seven points:

1) **Cover the river basin.** They should encompass the entire basin and cover all

Box 3. Using a mixture of detailed and meta-analysis EFlows Assessment methods

In the 1990s, South Africa completed several detailed EFlows Assessments using the Building Block Methodology (BBM). The results from these assessments were used to develop and calibrate the rapid Desktop Model (Hughes and Münster, 2000). Outputs of the Desktop Model were then used country-wide in water resource planning. Detailed EFlows Assessments continued in South Africa up to 2018, and the outputs from more than 50 rivers were used to update the calibration of the Desktop Model (Hughes and Hannart, 2003; Hughes *et al.*, 2013). The upgraded model was then used to increase the spatial coverage of assessments across the country as part of the move into Classification (Dollar *et al.*, 2010).

relevant river ecosystems (including riparian wetlands and floodplain, as applicable) and the estuarine ecosystem.

2) **Consider basin complexities.** Engage meaningfully with the complexities of river and estuarine ecosystems and the pressures they face, and use all available knowledge to evaluate the complex trade-offs inherent in developing, managing and restoring river ecosystems.
3) **Involve data and models as appropriate.** They should be based on:
    a. long-term daily hydrological time series (including consideration of geohydrological data as available/appropriate) and sub-daily hydrology if the scenarios include hydropower plants that will only generate power during peak demand periods;
    b. hydraulic/hydrodynamic modelling of rivers, floodplains and estuaries, as appropriate; and
    c. water-quality and sediment modelling, as appropriate.
4) **Include sediment, nutrient and ecosystem services.** They should consider:
    a. sediment supply, as this is a vital component of the link between river/estuarine ecosystems and the marine environment;
    b. nutrient status and provision of organic materials, as this is a vital component of the link between river/estuarine ecosystems and the marine environment; and
    c. a full suite of aquatic biota, including migratory species; and
    d. the knock-on effects of changes to the rivers and estuaries for the near shore environment.
5) **Use either holistic or ecosystem-modelling methods.** These need to have sufficient flexibility to respond to:
    a. scenarios representing different levels of basin development and use, expected changes in magnitude, duration and frequency of floods and droughts associated with climate change;
    b. management changes, such as limits on sediment mining, resource harvesting (e.g. fishing) and/or pollutants in effluents entering the system; and
    c. operating rules of water-resource infrastructure, in particular hydropower dams.

Plate 5. Surveying cross-sections across the Zambezi River.

6) **Establish data and knowledge management protocols.** Organize the available knowledge in a transparent manner that allows for immediate use and provides a platform for testing assumptions, improvement and verification of relationships, teaching and dissemination to local stakeholders.
7) **Ensure local knowledge is captured and the content strengthened.** Maximize use of in-country expertise to ensure that local wisdom is captured, that the value brought by local stakeholders and experts is acknowledged and supported, that prevailing concerns are incorporated into models, and that local capacity and understanding at all levels are strengthened.

4.3 EFlows Assessment team

Depending on the scope, budget and method, EFlows Assessment teams include specialists with a range of skills, such as:

- hydrologists who provide reliable measured or simulated hydrological times-series at an appropriate time for every point of assessment;
- eco-hydraulicians who translate discharge data into an understanding of the conditions that will affect biota, such as depth, velocity, shear stress, and area and duration of inundation;
- estuarine hydrodynamic modellers who translate river flow patterns into an understanding of changes in mouth state and salinity regime, shifts in water levels and tidal exchange that affect biota;
- sedimentologists and geomorphologists who understand:
  - the physics of river functioning and the links between sediments, water flows and their effects on the array of physical habitats of importance to people and riverine biota.; and
  - the interaction between coastal sediment processes and river sediment dynamics in estuaries and their effects on other physical and biotic processes.
- marine and freshwater quality specialists who understand the chemistry of river/estuary functioning and its links with the flow of water, sediments, and how these change as a consequence of pollution;
- biologists with expertise in: riparian and aquatic vegetation; aquatic invertebrates; fish; herpetofauna; water birds; river-dependent terrestrial mammals and who understand the links between between water flow, physical habitats, food sources, life histories of riverine species, and how all of these interact;
- fisheries scientists who can translate biotic responses into consequences for peoples' food security and livelihoods; and
- social scientists and economists who understand the social and economic implications of the biophysical predictions of change.

The specialists needed for a comprehensive EFlows Assessment at the basin level, comprising approximately 13 principle skills sets and responsibilities, are described in Table 9.

4.4 Spatial and temporal units of assessment

4.4.1 Site selection

Selection of sites/locations is an important aspect of an EFlows Assessment for rivers. Sites along the river are foci for bringing together the ecological (hydrological, sedimentological, hydraulic, chemical and biological) information and predictions of change and/or EFlows recommendations. The number of sites is dictated by finances, but also depends on the geomorphological variability of the river system, the location of developments such as dams or cities, social uses of different parts of the river, and more. A general aim is to cover the whole of the river study area through sites that can represent the different sets of conditions prevailing in the basin. Criteria for selecting sites include:

- representation and habitat diversity;
- availability of hydrological data at the required resolution;
- location and levels of impact of developments or management interventions;
- access and safety.

If the social implications of a changing river are to be included in the EFlows Assessment, then a similar study of social conditions should be done.

This would lead to the basin being divided into geographical areas, each of which differs in terms of how the river system is used. Each such area should be represented by an ecological site, with the ecological-social groupings sometime called Integrated Units of Analysis (Dollar *et al.*, 2010).

For the river basin of interest, the process followed could be to gather as much information as available, for any points along the system, on the following:

- a delineation of the aquatic ecosystems in the basin, which identifies similar river reaches and delineates the boundaries of wetlands, lakes, floodplains, the estuary and nearshore marine environment, as applicable
- location, reliability, record length and time-steps of recorded hydrological data;
- sediment audit and an interpretation of sediment sources and sinks in the basin;
- geomorphology of the system, including habitats available in different river reaches
- water quality characteristics;

Table 9. Potential members of an EFlows Assessment technical team.

TEAM MEMBER(S)	SKILL SET	RESPONSIBILITIES
Technical lead	• Project/team management • EFlows concepts and theory • EFlows Assessment methods/modelling • Integrate findings of river, wetlands, estuary, groundwater assessments	• Design and manage EFlows process • Implement EFlows methods/models • Quality assurance • Integrate technical reports • Communication
Hydrologist	• Hydrological modelling	• Source and prepare baseline data • Quality control
Water-resource modeller	• Water-resource modelling • Current and projected water resource development/use	• Model hydrological, sediment and water quality data for scenarios
Eco-hydraulician/ estuarine hydrodynamics	• Surveying • GIS/remote sensing and satellite imagery interpretation • Hydrodynamic modelling of open channels/estuarine processes	• Source, review and prepare topographic and other data • Model hydraulic and hydrodynamic relationships
Geomorphologist	• Geology • Sediment transport • Fluvial geomorphology • Coastal processes	• Source, review and prepare baseline data • Predict future responses of habitats to abiotic drivers • Provide reasoning
Water quality Expert	• Water quality in aquatic ecosystems • Relevant scientific literature • Links with sediment and water flows	• Source, review and prepare baseline data • Point and diffuse pollution sources • Recommend limits for sources of pollution
Micro-algal ecologist	• Phytoplankton and benthic micro-algae ecology (e.g. life history /tolerances) • Relevant scientific literature • Field sampling techniques and analysis of data • Links with sediment and water flows	• Source, review and prepare baseline data • Predict future responses to abiotic drivers • Indicate potential to have wider impacts (fish kills, toxic blooms, noxious smells)
Botanist	• Riparian and instream vegetation ecology (e.g. life history /tolerances) • Relevant scientific literature • Field sampling techniques, and analysis of data • Links to sediment and water flows	• Source, review and prepare baseline data • Predict future responses • Indicate potential for pest species • Provide reasoning
Macro-invertebrate ecologist	• Macro-invertebrate ecology (e.g. life history, tolerances) • Field sampling techniques • Relevant scientific literature • Links with sediment and water flows, and connectivity	

TEAM MEMBER(S)	SKILL SET	RESPONSIBILITIES
Fish ecologist	• Fish ecology (e.g. life history, tolerances) • Field sampling techniques • Relevant scientific literature • Links to sediment and water flows and connectivity	• Source, review and prepare baseline data • Predict future responses • Provide reasoning
Fisheries expert	• Species targeted by fisheries (fish and other taxa) • Level of use (tonnage, stock status) • Links to food production/security	
Social expert	• Ecosystem services • Relevant literature • Links to aquatic ecosystems • Region/social cohesion/international agreements	
Public health expert	• Health profiles and water-related diseases (water-borne, water-washes, etc.) • Relevant scientific literature • Links to water quality, vectors	
Other specialists	• Other specialists as required, e.g. ornithologists, mammologists, herpetofauna ecologists, economists, agronomists.	

- biotic characteristics, including any known links between species and favoured habitats;
- demographics and socio-economic development in the basin and along the river, including physical interventions such as urbanization, floodplain infilling, dam construction, major abstractions, types of agriculture, sources of pollution; (may be possible using available spatial data and Google Earth); and
- type and current level of resource use and valued ecosystem services.

The description of the different aspects of the basin should be provided by specialists, each with a high proficiency in their discipline, and an understanding of the dynamic interrelation between climate, hydrology, hydraulics, geomorphology, water quality, ecology and society.

Estuarine EFlows Assessments usually encompass the whole estuarine ecosystem. Small estuaries may be sub-divided into lower, middle and upper spatial units, and larger systems are generally zoned into homogenous units of representative salinity regimes and/or habitats.

4.4.2 Time-scales for analysis

EFlows Assessments are based on long-term hydrological and sediment time-series data sets, whether recorded, modelled or estimated, against which ecosystem changes linked to flow changes can be assessed. These kinds of data sets cannot be created in an EFlows Assessments, which are relatively short-term activities, and should be an integral part of routine data collection for management of river systems (Brown and King, 2002).

Systems with inconsistent flow regimes will need to use longer data sets for evaluation. For instance, if a river flow regime was about the same year on year, every year, then meaningful patterns and summary statistics could be discerned using a short record, as there would be little variation to account for, and the record would need only to be long enough to capture the main phases in the life cycles of indicator organisms (e.g. 5-6 years). For perennial and seasonal rivers with a fair to high predictability, the standard recommended minimum length of hydrological record for use in an EFlows Assessment is 20 years, with 50-60 years cited as preferable (King and Brown, 2009a). For these rivers, ecologically-relevant hydrological data are usually summarized per year or per season. For ephemeral or intermittent rivers with unpredictable periods of flow that are better summarized over decades rather than years, longer periods of evaluation may be needed.

4.4.2.1 Climate change

The assessment of climate change impacts may also necessitate longer assessment sequences, as the flow regimes of many rivers are becoming more unpredictable in the face of increased temperatures and variability in rainfall (Datry *et al*., 2017). One of the key aspects of climate change evaluation is to determine how an ecosystem would react to extreme events such as prolonged drought and/or more frequent high magnitude floods. In such instances, input time-series of sufficient length to capture historic droughts and or floods are invaluable in calibrating the response of the ecosystem.

4.4.2.2 Sediment

Predictions of changes in sediments also require a long evaluation period because changes linked with, for instance, sediments being trapped in a new dam reservoir may take years to decades to manifest as change in the downstream river. In these situations, the choices are to extend the period of the dataset used for evaluation or to accept that the predicted changes represent a slice in time and not necessarily the full spectrum of possible change.

4.4.3 Baseline conditions

All EFlows Assessments are constructed around a set of baseline conditions for the aquatic ecosystem under evaluation. In some cases, the baseline is chosen as near natural conditions (e.g. pre-1750 is often used in Africa and by the IUCN (Rodríguez *et al*., 2011)). More recently, conditions at the time of assessment are often taken as the baseline, as these are what people can measure and relate to. Predictions and/or recommendations arising from the EFlows Assessment are almost always relative to the chosen baseline conditions. Thus, the more comprehensive and accurate the data used to describe the baseline conditions, the more comprehensive and accurate the outputs of the EFlows Assessment.

An assessment of past and future trends in ecosystem components, such as hydrology, water quality, channel shape and the species composition is useful in establishing historical context and building an understanding of how they have responded to past pressures. This understanding assists in selecting the conditions to be used as a baseline for predictions and in developing common understandings of past pressures and their implications for ecosystem condition.

4.5 Stakeholder engagement

Engagement with stakeholders throughout the EFlows process is a fundamental requirement of IWRM. They should be identified through a structured and transparent process, together with their responsibilities, actual or potential involvement with EFlows, and their point of engagement, e.g. local, provincial or national. The objective is to identify their key areas of interest or concern (Box 4) and ensure such concerns are incorporated in each scenario and other outcomes of the assessment. In particular, it is important to:

- identify and engage key stakeholders early in the process so that they understand and support the nature of the assessment; and
- engage in capacity- and trust-building processes, such as field visits; participatory mapping exercises; and training sessions on the EFlows Assessment approach, its strengths and limitations, the nature of the expected outputs and the basics of aquatic ecosystem functioning.

Stakeholders should be involved at every stage in the process, including on a/an:

- agreement on the study areas and key ecosystem units in need of detailed investigations;
- design of scenarios for evaluation that include specifications for water-resource developments, abstractions, restoration initiatives and offsets, as appropriate;
- selection of indicators that reflect their areas of concern, such as the abundance of a fishery or of vectors of water-borne diseases;
- pre-agreement on criteria for evaluating scenarios, such as a limit to the drop in ecological condition for development scenarios; a target condition for rehabilitation initiatives or a limit to the change in any one species/guild/social use, such as a 10% reduction in fish catch or no-nett loss in biodiversity; and
- suggestions for future ecological condition, associated EFlows commitments, and other related management or mitigation measures.

The importance of effective engagement cannot be over-emphasized. Development-driven changes in river and estuarine ecosystems affect a wide range of stakeholders, and decisions on how much water to leave in the river for ecosystem support

Box 4. Stakeholder analysis, database and tracking

In their broadest sense, EFlows Assessments concern the relationship between the quantity and quality of the flows of water, sediment and biota through the environment and the ecosystem health, land use, stakeholder interests (e.g. farmers or municipalities), water-related institutions (e.g. water supply and waste-water management), and cross-cutting relations between these groupings (Warner, 2006). Effective stakeholder engagement necessitates a clear definition of which of these relations are relevant within the study area of an EFlows Assessment and the spatial level at which they may be relevant, e.g. local, provincial, national. This information can be generated through a basic four-step process (after Van Schoik *et al.*, 2004):

STEP 1: Identify stakeholders and their roles, objectives and scope/scale of action. This should include: name; key members; mandate and mission; role and responsibilities; interest and objective; interface with the study basin and the scope or scale of that interface; constraints with respect to uptake of the Project outcomes; alliances/interactions with other stakeholders, and the nature of such relationships; contact details and social media presence/preferences.

STEP 2: Stakeholder analysis. Group and arrange stakeholders according to their interests, mandates, etc. and identify the kinds of information/interactions and evidence-based materials that would enhance their engagement with the EFlows Assessment. Incorporate less-defined aspects such as capacities, power dynamics, institutional constraints and opportunities with respect to how they contribute towards the goals of the EFlows Assessment, its outcomes, and implementation of such outcomes.

STEP 3: Stakeholder mapping: Use recognized mapping techniques such as Venn diagrams, organograms and flow charts to visually depict the relations between the stakeholders with respect to interests, size, roles, mandates and information requirements.

STEP 4: Stakeholder tracking. Record interactions, such as meetings, workshops, telephone calls and emails with each stakeholder in a database on an ongoing basis throughout the project, including comments or suggestions received, activities to address such input, and and changes to the individuals representing stakeholder groups.

and how much to use for alternative benefits often involve difficult trade-offs (Section 2.4). Stakeholder involvement requires thorough design and planning, and depending on the situation and context, may include a range of different stakeholder engagement and public participation methods.

Instruction on the background and concepts of EFlows and the way in which they are determined is a valuable investment, allowing all to absorb the philosophy, nature and reason for flows for ecosystem support; understand the potential trade-offs and other implications of development at all scales from local to international; and explore new ways of managing water resources so as to arrive at more balanced and equitable development decisions. Ideally, there should be close collaboration between:

- the EFlows technical team
- the water managers and decision makers
- the water engineers
- the dam owners and dam operators
- the wider stakeholder groups.

4.6 Scenarios

Well-designed scenarios that encompass a wide range of possible futures for river basins allow the evaluation of a wide range of conditions, typically:

- the cumulative effects of proposed management options and development projects;
- the barriers to flow, sediment and biota that would be the least or most destructive;

- which tributaries could best be developed and which conserved with natural flows and fish migrations;
- the ecological and associated social benefits of restoration initiatives aimed at improving water quality and/or reducing catchment erosion;
- the configuration, design and operation of dams that would best promote biodiversity and support fish populations;
- how much water in what pattern of flows would be required to maintain different parts of the river system at various levels of health (King and Brown, 2018); and
- how climate change may affect these.

It is imperative that scenarios be chosen in consultation with the government/client/stakeholders to avoid the findings being dismissed as irrelevant. They should be internally coherent (IPCC, 2007), so that, for instance, if more water is to be impounded for agricultural development and urban growth, more return flow would most likely enter the system as agricultural return flow or even as waste water, thus elevating baseflows and affecting water quality.

The added influence of wetter, drier or more extreme climatic conditions as a result of climate change can be evaluated in an EFlows Assessment through its inclusion in scenarios. Most scenario-based EFlows methods can incorporate climate change predictions provided the changes in the flow regime, can be simulated via a Climate Change Model and a Rainfall-Runoff Model (WBG, 2018). Scenarios run with and without climate change included can illustrate its additional impact.

4.7 Biophysical and social indicators

Indicators are the attributes of the system that are used to describe change. They will usually be aspects that are responsive to changes in the flow or sediment or water quality regimes. The discipline specialists in the team will select indicators as appropriate, such as the biophysical and social ones listed in Table 10, taking note of the concerns of stakeholders and trying to address these. If, for instance, a stakeholder is concerned that specific favoured fish species or reeds could be lost with a water-resource development, such a matter could be listed as an indicator. All scenarios subsequently produced will then predict their expected change from the baseline.

4.7.1 Mapping indicator links

For those assessment methods leading toward the construction of an ecosystem model, mapping the links between indicators – i.e. drivers and responders – is a vital and very insightful exercise. Each of the links shown in the map will become a response curve drawn by the EFlows team, which describes the relationship between driver and responder (Figure 9). This is the fundamental material used when creating an ecosystem model, which can be updated as data and understanding increase (Brown *et al.*, 2013).

4.8 Data requirements

There are three main kinds of data used in EFlows Assessments: physical/chemical, biological and social. These can be divided into driving indicators and responding indicators, although feedback loops mean that some responding indicators become driving indicators. For example, a change in flood magnitude (driver) could reduce floodplain inundation and thus affect the zones of floodplain vegetation (responders). The floodplain vegetation indicators then become drivers that affect the grazing of herbivores (responders), which could then drive change in household food security or tourism.

The older and coarser assessment methods tend to need fewer data and fewer kinds of data than the modern and more complex methods. Table 11 and Table 12 summarize some of the basic data/information required for the EFlows Assessment of rivers and estuaries.

4.8.1 Physical/chemical

4.8.1.1 Hydrology

The primary input data to an EFlows Assessment are always hydrological in nature – flow in river channels or inundation of floodplains and estuaries. The aim is to describe the past and present hydrological nature of the system to the best extent possible, as the basis upon which to

Table 10. Example of biophysical EFlows indicators used for a site on the Zambezi River (Southern Waters, 2019b) and for the Great Berg Estuary (DWAF, 2010).

DISCIPLINE	INDICATORS	DISCIPLINE	INDICATORS
Zambezi River		**Great Berg Estuary**	
Hydrology (sub-set)	Dry season onset	Hydrology	Average discharge
	Dry season min 5-day discharge		Dry season onset
	Dry season duration		Dry season duration
	Dry season average daily volume		Dry season average discharge
	Wet season onset		Wet season onset
	Wet season duration		Wet season duration
	Wet season maximum discharge		Drought average flow rate
	Wet season flood volume		Drought duration
			Flood volume
Hydraulics	Width/wetted perimeter		Flood duration
	Depth	Hydraulics	Mouth state
	Mean velocity		Water levels
	Mean shear stress		Tidal amplitude
Suspended sediments (SS)	Dry: min/max/mean Coarse SS		Tidal flow rate
	Dry: min/max/mean Fine SS		Salinity structure/mixing processes
	Wet: min/max/mean Coarse SS		Extend of inundation of floodplain
	Wet: min/max/mean Fine SS	Suspended sediments (SS)	Dry: min/max/mean Coarse SS
Geomorphology (habitat)	Low mid-channel rock exposures		Dry: min/max/mean Fine SS
	Lengths of cut marginal banks		Wet: min/max/mean Coarse SS
	Backwater bed sediment size (fine to coarse)		Wet: min/max/mean Fine SS
	Area of backwaters and secondary channels	Geomorphology (habitat)	Area of backwater and secondary channels
	Vegetated mid-channel bars		Sediment structure
	Channel bed sediment size		Open water habitat
	Depth of pools		Area and sediments structure of subtidal habitat
	Sand bars		Intertidal habitat (area and sediment)
Water quality	Nutrient concentrations		Supratidal habitat (area and sediment)
	Temperature		Floodplain habitat within estuary functional zone

DISCIPLINE	INDICATORS	DISCIPLINE	INDICATORS
Zambezi River		**Great Berg Estuary**	
Vegetation	Single-celled diatoms	Water quality	Salinity
	Filamentous green algae		Temperature
	Bryophyta		pH
	Marginal graminoids/shrubs		Dissolved Oxygen
	Lower bank riparian trees		Dissolved Inorganic Nitrogen
	Upper bank riparian trees		Dissolved Inorganic Phosphate
	Organic detritus		Dissolved Reactive Phosphate
Macroinvertebrates	Ephemeroptera		Dissolved Reactive Silicate
	Bivalves	Microalgae	Phytoplankton
	Oligoneuridae		Benthic microalgae/microphytobenthos
	Chironomidae	Macrophytes	Macroalgae
	Simulidae		Submerged macrophytes
	Ceratopogonidae		Intertidal salt marsh
	Shrimps/prawns		Supratidal salt marsh
Fish (sub-set)	Hydrocynus vittatus		Reeds and sedges
	Mormyrops anguilloides	Invertebrates	Copepods
			Mysids
	Labeo cylindricus		Carid shrimps
	Cichlids		Sandy subtidal benthos
	Distichodus spp		Muddy subtidal benthos
	Labeo altivelis	Fish	Estuarine residents
	Heterobranchus longifilis		Estuary dependent marine species
	Squeaker, Synodontis zambezensis		Marine migrants
			Euryhaline freshwater species
Crocodiles	Nile Crocodile, Crocodylus niloticus		Catadromous species
		Birds	Herbivorous waterfowl
			Omnivorous waterfowl
			Piscivorous waterfowl
			Wading/swimming piscivores
			Perching/aerial piscivores
			Flamingos (Greater, Lesser)
			Macrobenthos-feeding waders
			Piscivorous gulls and terns

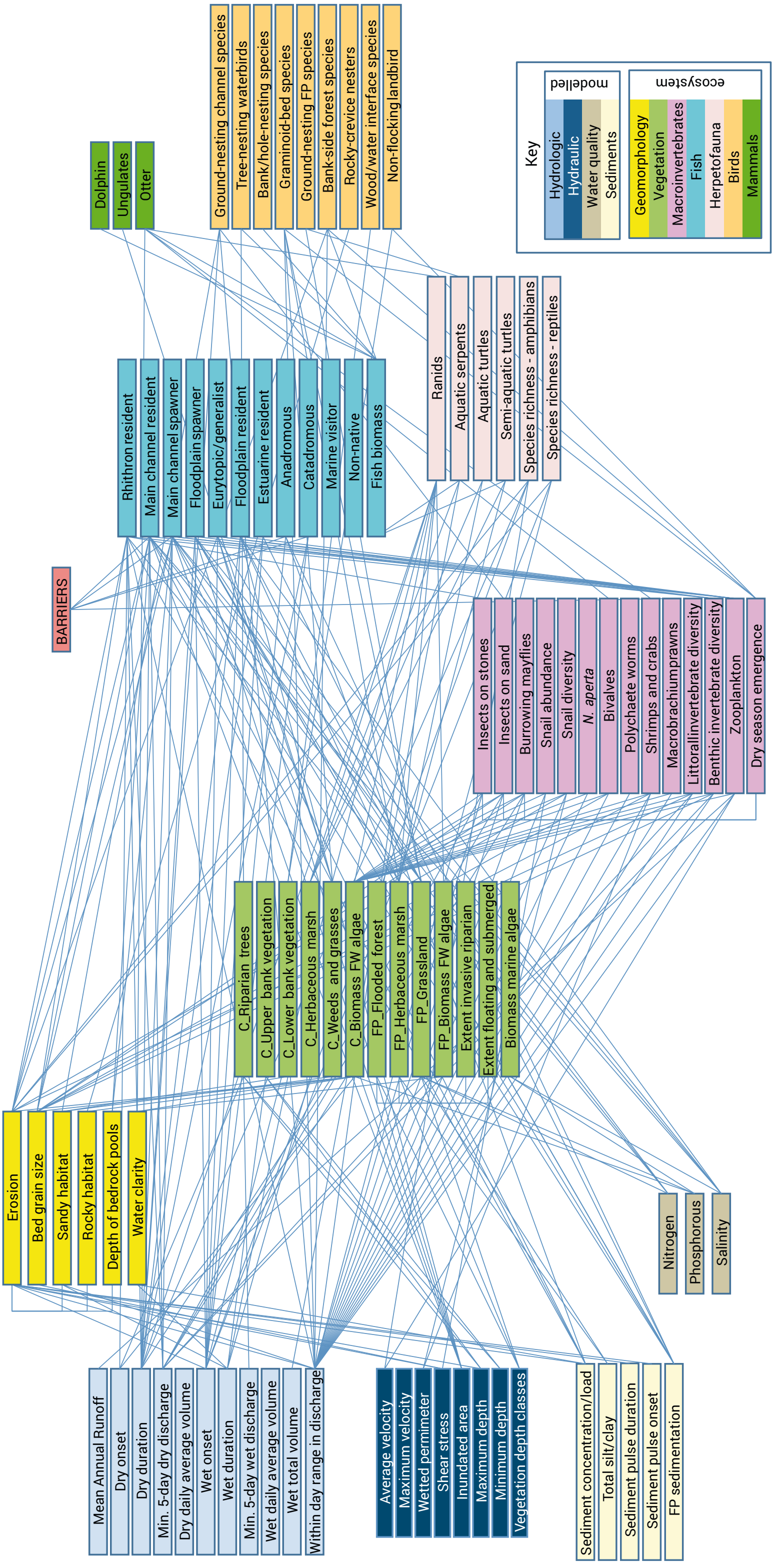


Figure 9. An example of linked indicators for a river ecosystem (Mekong River, SE Asia (MRC, 2017)).

build the geomorphological, chemical and biological picture. The finer the detail, the better the chances of building good basin models with which to predict human-driven or climate-driven change.

However, it is important to note that the nature and time-step of the hydrological data are important but differ significantly between EFlows Assessment methods. In each case, the assessment can only consider changes relative to the input data, and factors not included are assumed to be unaffected, i.e. assumed to remain at baseline conditions. For instance, if the chosen EFlows method uses monthly hydrological data, the (usually unstated) underlying assumption is that the onset or duration of different flow seasons will be the same as in the baseline situation, because any changes in onset and duration can only be evaluated using daily hydrological time-series. Coarse monthly data also translate into uncertainty about lateral and longitudinal connectivity of the system, the nature of dam releases, and the impacts on the ecosystem and people.

Ideally, 30-60 years of measured or simulated daily hydrological data are needed for each EFlows site along a river system. Annual or monthly data do not capture the variability and seasonal patterns that affect the life histories of most river organisms and the livelihoods of riparian people. The daily data can then be summarized to produce ecologically-relevant hydrological statistics (Table 13). Hourly data are needed when predicting the effects of a peaking-power hydropower dam, which result in large sub-daily variations in discharge. In estuaries, time-series of water level at five to ten minute intervals are used to develop an understanding of the dynamic interactions between river inflow and the tidal cycle.

Plate 6. Mbwemkuru River discharging to the Indian Ocean at Msungu Bay, southern Tanzania.

Table 11. Basic data/information used for five different EFlows Assessment methods for rivers (after WBG, 2018; van Niekerk *et al.*, 2019).

DATA – SEVERAL INDICATORS COULD BE IDENTIFIED WITHIN EACH MAIN INDICATOR GROUP BELOW			TENNANT	DESKTOP	BBM	HFSR	DRIFT
Physical and chemical							
Driving	Hydrology	Time-series of discharge at locations of interest for natural, baseline and projected future (scenario) daily flow regimes	Natural	Natural	Natural	Natural	Baseline
		Monthly or daily time-step	Monthly	Monthly	Daily	Monthly	Daily
		Hourly time-step for evaluation of peaking power hydropower dam operations	NO	NO	NO	NO	YES
Driving	Connectivity	Barriers and loss of longitudinal and lateral connectivity	NO	NO	NO	NO	YES
	Sediments	Long-term, ideally ≥50 years, time-series of sediment size and loads for natural, baseline and projected future at sites of interest.	NO	NO	NO	NO	YES
	Water quality	Long-term time-series at minimum dissolved solids, nutrient concentrations and temperature. Long-term time-series for these are invaluable, but in their absence some indication of the prevailing water quality can be utilized.	N/A	N/A	YES	YES	YES
Responding	Hydraulics	Depths and velocities in the river channel; depths or area of inundation on a floodplain for key sites.	NO	NO	YES	YES	YES
	Geomorphology	Availability and distribution of key aquatic habitats; bank erosion and other vulnerable channel features at sites of interest.	NO	NO	YES	YES	YES
Biological							
Responding	Plants	Abundance, species composition, distribution and recruitment of key riparian and aquatic plant communities and links to flow.	NO	NO	YES	YES	YES
	Invertebrates	Habitat and species conservation status, abundance, distribution and recruitment (including migration routes and timing) of species of concern, and links to flow.	NO	NO	YES	YES	YES
	Fish		NO	NO	YES	YES	YES
	Other river-dependent fauna.		NO	NO	YES	NO	YES

DATA – SEVERAL INDICATORS COULD BE IDENTIFIED WITHIN EACH MAIN INDICATOR GROUP BELOW			TENNANT	DESKTOP	BBM	HFSR	DRIFT
Social							
Responding	Subsistence needs	The level of dependence of the local people on riverine resources; what resources (see Plate 7) are used; from where and when.	NO	NO	YES	NO	YES
	Public Health	Health concerns linked to the river, e.g. river-borne diseases or dangers from wildlife, such as hippos and crocodiles.	NO	NO	NO	NO	YES
	Livestock Health	Health concerns linked to the river, e.g. river-borne diseases or dangers from wildlife, such as hippos and crocodiles.	NO	NO	NO	NO	YES
	Culture and recreation	Cultural and recreation use of the river, including: features used, e.g. waterfalls, pools or riffles; time of year; degree of contact with the water; known dangers.	NO	NO	YES	NO	YES

Plate 7. Fish landing site on creek into Lake Jipe, bordering Kenya and Tanzania.

Table 12. Basic data/information requirements for five different EFlows Assessment methods for estuaries.

DATA			% FLOW METHOD	VEC METHOD	RSA ESTUARY DESKTOP	RSA ESTUARY DETAIL	DRIFT
Physical and chemical							
Driving	Hydrology	Monthly river discharge at head of estuary for natural, baseline and scenarios	YES	YES	YES	YES	YES
		Daily river discharge at head of estuary for natural, baseline (as close to current as possible) and projected future daily flow regimes	NO	NO	NO	NO	YES
		Hourly time-step for evaluation of flood hydrograph (return period 1:1 to 1:200 years) and dam operations at head of estuary	NO	NO	NO	YES	YES
	Sediment dynamics	Sediment size and loads at head of estuary for natural, baseline and scenarios	NO	NO	NO	YES	YES
	Wave conditions	Wave condition data (as reflected by direction and amplitude of the waves) used to correlate mouth closure with possible storms at sea.	NO	NO	NO	YES	NO
	Water quality	Water quality of river inflow: system variables (pH, DO, turbidity, suspended solids, TDS and temperature), nutrients (inorganic nitrogen [nitrite, nitrate, ammonia], reactive phosphate and silicate) and toxic substances (where relevant)	YES	NO	NO	YES	NO
		Water quality of the nearshore marine waters. Obtained from available literature.	NO	NO	NO	YES	YES
		Effluent discharges, composition and volume over time	NO	NO	NO	YES	NO
Responding		Water quality in estuary: Spatial and temporal distribution of salinity and temperature, plus other water quality parameters (see above) in surface and bottom waters.	YES	NO	NO	YES	NO
		Toxic substances: Spatial distribution and extent of toxic pollutants in the estuary	NO	NO	NO	YES	NO
	Hydrodynamics (mouth state)	Satellite imagery and historical aerial photos (< 1930s) of channel ration and mouth dynamics	NO	NO	YES	YES	NO
		Continuous water level /tidal amplitude recording near the mouth and every 10 to 20 km thereafter, depending on length of the system.	YES	YES	NO	YES	NO
	Sediment dynamics / Geomorphology	Estuary bathymetric/topographical surveys and core/grab samples	NO	YES	NO	YES	YES
		Toxic substances, grain size distribution and organic content e.g. in runoff from urban or industrial areas or contaminated agricultural runoff.	NO	NO	NO	YES	NO

DATA			% FLOW METHOD	VEC METHOD	RSA ESTUARY DESKTOP	RSA ESTUARY DETAIL	DRIFT
Biological							
Responding	Microalage	Species richness, abundance and community composition	YES	YES	NO	YES	YES
	Macrophytes		YES	YES	YES	YES	YES
	Invertebrates		YES	YES	NO	YES	YES
	Fish		YES	YES	YES	YES	YES
	Birds		NO	NO	YES	YES	YES
Social							
Responding	Fisheries requirements	Extent of estuarine and coastal recreational and /or commercial fisheries.	NO	YES	NO	YES	YES
	Subsistence needs	The level of dependence of the local people on estuarine resources; what resources are used; from where and when.	NO	NO	NO	YES	YES
	Public Health	Health concerns linked to the estuary, e.g. water-borne diseases, nuisance algal blooms, pathogens and parasites in fish.	NO	NO	NO	YES	YES
	Livestock Health	Health concerns linked to the river in upper research of estuaries, e.g. river-borne diseases or dangers from wildlife, such as hippos and crocodiles.	NO	NO	NO	NO	YES
	Culture and recreation	Culture and recreation use of the estuaries, including: features used, e.g. baptism sites, degree of contact with the water; known dangers.	NO	NO	NO	YES	YES
Driving	Management considerations	Mouth state requirements, water level requirements, waste water discharge permits, flow release requirements to maintain a prescribe estuary condition (e.g. open mouth in summer)	NO	YES	YES	YES	NO

4.8.1.2 Hydraulics

Channel hydraulics describe how water flows through the system at different discharges. In their simplest form, hydraulic measurements can produce simple stage-discharge curves that indicate water depth at any discharge. With increasing complexity, more information can be gleaned of how the ecosystem functions: through routing discharge events down the river channel and modelling inundation levels of floodplains, to full basin hydrological models, or complex hydrodynamic models of estuarine environments under the influence of both river flow and tides. For more complex hydrodynamic models, run time is an important factor as typically long (>30 years) time-series associated with scenarios of future flow options are needed. As with the hydrological data, the hydraulic data can be summarized in an ecologically-relevant form.

For estuaries, the hydrodynamic modelling inputs should include all tides and all flow regimes (historical, present and proposed future) to evaluate the responses of the system to extended periods of low flow (months to years). This allows accurate simulation of salinity levels under the influence of

Table 13. Examples of ecologically relevant summary statistics that can be calculated from hydrological time-series of different time-steps (shaded = can be calculated).

STATISTIC	TIME-STEP			
	ANNUAL	MONTHLY	DAILY	HOURLY
Mean annual runoff	▨	▨	▨	▨
Minimum dry season flow			▨	▨
Mean dry season flow		▨	▨	▨
Maximum wet season flow			▨	▨
Mean wet season flow		▨	▨	▨
Peak and duration of flood events			▨	▨
Duration of seasons			▨	▨
Onset of seasons			▨	▨
Within day fluctuations in discharge				▨

tidal action and diffusion. The model should also cover the entire estuary and its floodplain to the outer limits of tidal action. The trade-off between accurate real-world representation and computational overheads determines whether to use 1-, 2- or 3-dimensional modelling. For instance, 3-D modelling may give the best real world representation, but has high computational overheads and long run times, and so for many systems 1- or 2-D modelling has proved to be the preferred option (Van Ballegooyen *et al.*, 2004).

4.8.1.3 Water quality

Long-term records on river water quality help development of a basin-level understanding of how aquatic ecosystems respond to changing conditions. This is particularly so in estuaries, where water quality along the length of an estuary varies seasonally and daily (Taljaard *et al.*, 2009) depending on the volume of river flow, residence time, the state of the tide and whether the estuary is open or closed to the sea (Taljaard *et al.*, 2009; DWAF, 2008). In practice, however, such records are often not available, and less-regular spot data are used. Depending on the availability of data, collection and analysis of bi-monthly composite samples (e.g. samples taken hourly over one day using a carousel sampler) from multiple sampling points, in combination with in situ measurements from installed meters may need to be incorporated into the EFlows Assessment. Ideally, sufficient data exists to set up a water quality model for the entire basin, which is the principle goal, but this is rarely possible in reality.

4.8.1.4 Sediment and geomorphology

Data on the volume and size-distribution of sediment (both along the bed and total suspended sediment (TSS)) supplied to a location at a daily or even monthly time-step are invaluable additions to an EFlows Assessment, but are rare. Inclusion of sediment dynamics in EFlows Assessment is in its early stage of adoption but it is important to include it at whatever level of resolution possible. Section 5 provides suggestions for situations where data are limited.

A geomorphological analysis of the nature of the river channel and available physical habitats should be undertaken in a way that allows relationships between geology, topography, flow, sediments and vegetation to be captured.

4.8.2 Biology

The above measurements and models provide the crucial initial information on the nature of the river channel and estuary and the conditions it affords plant and animal communities. The biological data included depends on the EFlows Assessment method used and the objective of the study but could focus on all major aspects: riparian, marginal and aquatic vegetation; aquatic invertebrates; fish; water birds; herpetofauna; and river-dependent mammals. Data on the life histories of these riverine and estuarine species inform critical life stages and conditions needed to complete these. It would normally be impossible to collect relevant data on all such biotic groups within a single EFlows Assessment. Instead a limited amount of focused data collection is normally combined with a range of other sources of knowledge:

- previous and/or published data collected from the river basin under consideration on life histories, preferred habitats, flow-related requirements;
- published data from similar rivers;
- expert opinion; and
- local wisdom.

4.8.3 Social

Baseline information on the social uses and values placed on ecosystem services provided by the river and estuarine system (Figure 2.1) is typically accomplished through a review of available information and discussions with stakeholders. This may be augmented through, for instance, key informants' interviews with a range of users and experts and market surveys. Changes in use over time should also be described, if possible, in relation to historical trends in the condition of these systems in order to better understand how a changing ecosystem has affected people.

The supply of and demand for the ecosystem services should be summarized based on an understanding of the dynamics of the ecosystem, local livelihoods, tourism activities, local and wider economic factors and surrounding land use. The variation in these services and their value down the length of the affected area should also be described where appropriate.

4.9 Field visits

Field visits by the whole team are a crucial part of a detailed EFlows Assessment. Nothing can replace the experience and value of standing on the banks of a river/estuary, with each expert describing what they see and understand about the system. Apart from the shared wisdom that builds up, the individual specialists can complete their work and modelling with a much greater intuitive understanding of how the system functions.

The visits are most fruitful if a first draft of all indicators and their links has already been completed (Section 4.7) for re-assessment at and after the field trip. This is particularly important for the social surveys, which are likely to significantly expand understanding of social uses of the system. The first visit should be during the low-flow season so that details of the river channel and habitats can be seen and measured.

The individual data-gathering guidelines are driven by the needs of the method adopted and are best developed with the EFlows Project Leader.

4.10 Set-up and calibrate EFlows models

Depending on the method chosen and the objectives, available models are set up and calibrated using existing measured or simulated data, or expert opinion, as follows:

- The water-resource model (essential) describes current hydrological conditions in the system and can be used to predict flow changes associated with potential development and management options.
- The ecohydraulic/hydrodynamic model (essential) describes the hydraulic manifestation of the flow regime as depths, velocities, shear stress and more.
- The water quality and sediment models, if available, describe current conditions and predict future conditions linked to potential development and management options.
- The more advanced EFlows Assessment methods have models or frameworks that store the relationships between the indicators (Section 4.7) and are used to predict the biophysical, biological and social implications of the potential development and management options. Once populated and validated, these models are then available for use in impact assessments, adaptive management and planning.

Most available models can be downloaded from the Internet; some are freely available while others have a cost.

4.11 Analyse the scenarios

The outcome of a detailed EFlows Assessment is likely to be a set of information for each site under each scenario. Typically the outcomes will include the following:

- summary of the hydrological, hydraulic and sediment status;
- predicted change of the full suite of indicators;
- predicted impact on indicators grouped in meaningful ways, such as on fish guilds or overall channel condition;
- predicted overall ecosystem condition for the affected aquatic ecosystems (Figure 4.2); and
- predicted impact on valued ecosystem services.

Figure 10 shows how the condition of rivers in the Okavango Basin will change from the baseline, where the rivers in the basin are in a near natural condition (health category B) under scenarios of low, medium and high water-resource development. This shows the severity and location of expected impacts on ecosystem functioning and allows developments that will result in largely or seriously modified ecosystems to be red-flagged.

In addition to the site information, the model outputs can be summarized at the basin level to provide a quick overall view of the differences between scenarios. These include:

- predicted impacts on grouped indicators, such as channel condition or fish diversity;
- predicted impact on overall ecosystem condition;
- predicted impacts on valued ecosystem services; and
- impacts on the three pillars of sustainability: ecological integrity, social equity and economic prosperity.

Stakeholders will require different levels of data presentation depending on what use they intend to make of the EFlows outputs. With this in mind, the results should be presented using non-technical language to the extent possible and the reasoning behind all predicted positive and negative impacts explained.

The choice of a scenario should be through a previously agreed-upon, structured and transparent process. The chosen scenario represents the trade-off between development and resource protection - a selected pathway of development or restoration. It defines the agreed-upon condition for each part of the river system, which can be used in monitoring for compliance, and also provides the EFlows required for ecosystem maintenance (King and Brown, 2009a).

4.12 Reporting

EFlows reporting comprises the following five elements:

1. Inception or Scoping Report, which lists the client, dates, terms of reference, location of team, the objectives of and approach to the EFlows Assessment, method choices with motivations, delineation and site selection, preliminary assessment of the health of the ecosystem(s), preliminary information on social uses and ecosystem services, team selection, field work schedules, and the work programme for the assessment.
2. Progress Reports, which detail ongoing work and issues requiring attention.
3. Specialists' Report, which should provide detailed background information for each discipline included in the EFlows Assessment (e.g. hydrology, hydraulics, water quality, sediments, biota and social), an assessment of the condition of the ecosystem(s), with supporting data and data analyses, explanations of models used and their inputs and outputs, indicators selected with explanations given. It should also include the reasoning underpinning the EFlows Assessment and evidence supporting the relationships derived (e.g. from data collected, the scientific literature or local knowledge), limitations and assumptions inherent for each discipline and sugges-

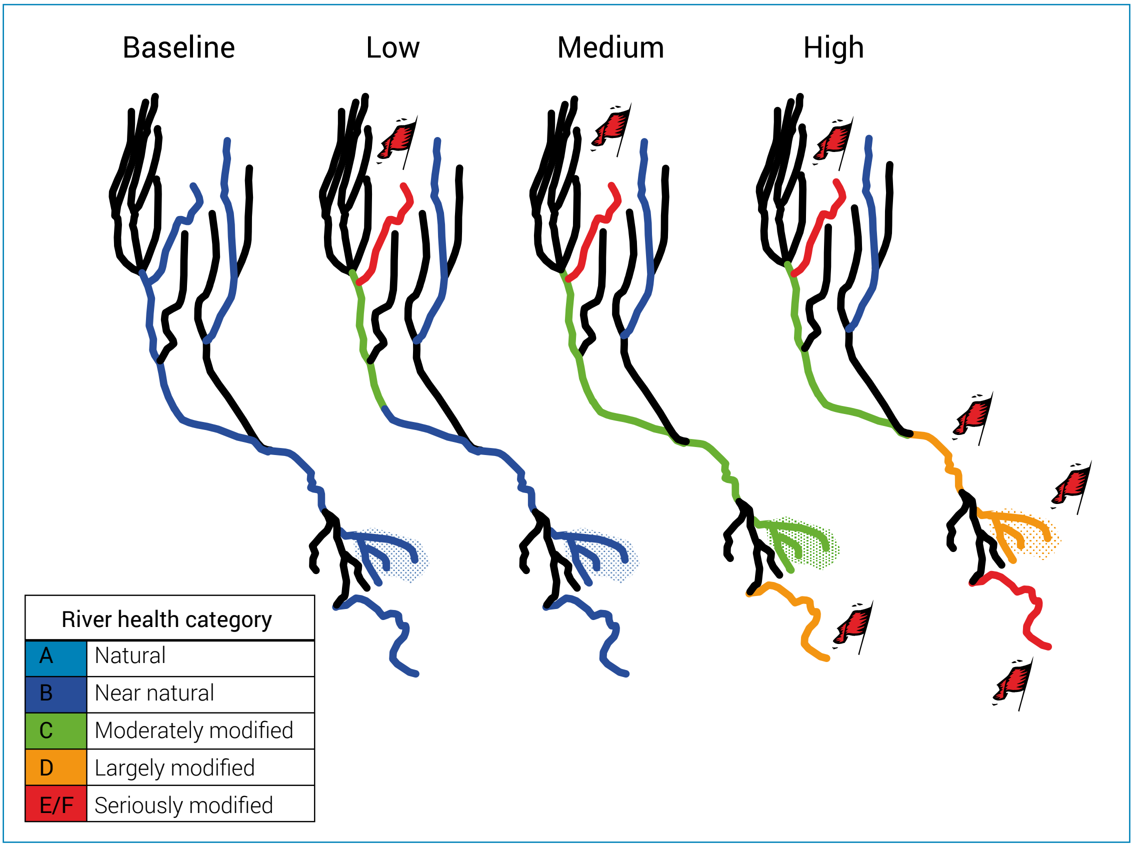


Figure 10. Example of basin-wide predictions of ecological condition for the Okavango River system under baseline and three scenarios of water-resource development (King and Brown, 2009b), with areas of potential concern 'red-flagged'.

tions for monitoring. It is also important to include a section on the use and value of riverine resources (e.g. from interviews) and the cross-links to the other disciplines.

4. EFlows Report, which describes the context of the EFlows Assessment, including sites/reaches and the indicators used to describe change and the links between them, the scenarios assessed, the predictions of change for individual indicators. It should also provide, in summaries relevant to the study area, an overview of impacts on the aquatic ecosystems, the limitations and assumptions applicable, conclusions of the scenario assessments, and key knowledge gaps and the options available for addressing these.
5. Final Report, which provides an overview of the work and its outputs, the financial summary and an assessment of the adherence of the project to its terms of reference.

Additional reports may be required once a decision on the allocated EFlows approach and model(s) to be used is made. Depending on the requirements of the client and/or government, these reports may take different forms. Common additional reports include: an Analysis of Additional Scenarios, a Monitoring Programme, a Notice for a Government Gazette (see Box 7, Section 6.5), and/or an Environmental Flows Management Plan (EFMP). An EFMP is a record of management actions and agreements related to EFlows. It describes the EFlows regime and other objectives agreed upon, the activities required for implementation, monitoring and review of the EFlows. It further clearly defines the responsibilities and key performance indicators (WBG, 2017).

4.12.1 Other deliverables

Most EFlows Assessments produce several other outputs in addition to the formal reporting. Common examples include:

1. Powerpoint presentations used for capacity building, project reporting and presentation of the results of the EFlows Assessment.
2. Training course materials
3. Datasets, such as the hydrological and hydraulic time-series for baseline and scenarios
4. Populated and validated EFlows model (if relevant for the method selected), with a User Guide.

Whether or not an assessment method will provide accurate predictions depends not only on the availability of accurate hydrological records, but also on the method's appropriateness for use; the quality of existing water quality, sediments and species data; and the training and knowledge of the EFlows Assessment team.

5. Managing data limitations

Whatever the method adopted, decisions will still be made with incomplete data and understanding, because new kinds of questions are being asked and data-poor situations are the universal reality. EFlows Assessment techniques have evolved to cope with such constraints, recognising that there is always something that can be done and that poor data availability should never be a reason for not undertaking an EFlows Assessment. Instead, where data are not available or are rare, the short-term option could be to rely on experienced specialists (e.g. Box 5). A key strength of the holistic and ecosystem-modelling methods developed in South Africa for African conditions (e.g. BBM, HFSR, RSA Estuary Method and DRIFT) is that they are able to incorporate any relevant knowledge and local wisdom and so, guided by an experienced EFlows practitioner, can be used in both data-rich and data-poor situations (e.g. Box 6).

Several methods address data unavailability by predicting a relative change in condition from the baseline. Changes in sediment supply, for instance, can still be evaluated in the absence of recorded or modelled data on sediments by setting the baseline level of sediments in the system as 100 percent and then exploring whether scenarios will cause an increase (e.g. 150 percent) or decrease (e.g. 50 percent) in baseline levels. Uncertainty can be addressed by showing the range of the prediction – the wider the range, the greater the uncertainty.

Some methods capture the predictions and range of uncertainty electronically using custom-built software. This provides consistency and transparency on the assumptions made and allows the relationships to be updated as understanding increases.

Box 5. Cost-effective means of generating sediment data

Expert knowledge and rapid characterization of catchments in terms of susceptibility to erosion are viable options for assessing changes in sediment supply from land-use (see Plate 8) and for analysing in-channel controlling factors, such as impoundments, with minimum costs and acceptable accuracy (Temane *et al.*, 2014).

Plate 8. Sand minining as see here for the Sabaki (Athi River) Estuary can significantly affect sediment supply.

Box 6. Challenges and solutions in EFlows Assessments for non-perennial rivers

(Seaman, *et al.*, 2016)

An EFlows team used a modified version of DRIFT to assess the EFlows of the non-perennial Mokolo River in South Africa. As part of the work, they identified the following six challenges and described the way in which they were met:

1. **Difficulties in simulating hydrological data.** There were few rain and flow gauges. Monthly simulated hydrological data could not be disaggregated to reveal the nature and timing of floods and the onset and end of low surface flows, resulting in data of low accuracy and confidence. Solution: Used catchment data, local knowledge and insights from soil scientists to better understand the hydrological functioning of the rivers.
2. **Understanding pools.** When surface flow stops, pools act as refugia for aquatic life, but their location, nature, water chemistry, and persistence are poorly understood, and so the response to scenarios was difficult to provide. Solution: Relied on local knowledge and indicators (invertebrates and fish that prefer pool habitat) for which data could be collected.
3. **Connectivity.** Pool connectivity is a key attribute of non-perennial rivers, allowing for movement of organisms, mixing of gene pools and transport of nutrients and sediments. Poor coverage of flow measurements meant the extent of connectivity was uncertain. Solution: Used an integrated groundwater and surface water model to predict when flow would be expected between pools, together with Runoff Potential Units that provided an indication of the runoff expected in different sub-catchments.
4. **Surface and groundwater interactions.** Solution: Used an integrated groundwater and surface water model.
5. **Extrapolation.** Extrapolation of relationships from other rivers was meaningless as understanding was limited mostly to the functioning of individual study sites. Solution: The only data used were those collected from each river reach.
6. **Establishing a reference condition.** Non-perennial rivers, being understudied and notoriously variable and unpredictable, do not easily yield a reference condition. Solution: A two-pronged approach was used: firstly, using historical data and landscape clues to estimate a natural/reference condition and secondly, using a baseline (present-day) condition as the starting point for scenario comparison, as that is what can be seen and measured.

6. Mainstreaming the uptake of EFlows Assessments

Environmental Flows are a tool for informing the allocation of water among multiple, competing uses in a river basin and building understanding and consensus on how to manage and develop river ecosystems. Developing and implementing EFlows is a long-term complex management process (Table 14). The uptake of EFlows Assessment outputs is enhanced by the inclusion of EFlows into water policies and law that recognize the values and ecosystem services provided by aquatic ecosystems. Also important are policies that support its implementation, including provision for the appropriate technical capacity, engaging stakeholders, setting standards, encouraging and supporting local experts, and establishing monitoring networks (Harwood *et al.*, 2018; King and Pienaar, 2011). These should include the need for a negotiated consensus on flow allocation among all stakeholders.

Arguably the most important is the need to encourage and support regional and national EFlows champions. These should be individuals with a background in aquatic ecology, geomorphology, hydrology or water-resource management/planning and a long-term commitment to enabling and implementing the EFlows process. Experience has shown that committed and effective champions are often the catalyst for initiating the other enabling factors (O'Keeffe, 2018). Ideally, two champions, or even a group, should be the aim. One should be from a government agency, preferably the one tasked with EFlows implementation, and the other(s) may be from a university, research institute, NGO and/or major stakeholder group (O'Keeffe, 2018).

6.1 Deciding on EFlows allocations

As mentioned in Section 2, the EFlows Assessment provides the scientific information on how river and estuarine ecosystems will change under various scenarios of water use. Stakeholders use this information to consider the costs and benefits of each scenario and negotiate the preferred future nature and condition of the river or estuary. There are many variations on how to achieve such an objective. In South Africa, the stakeholder process to select a desired future state for the water resources in a basin, the EFlows allocation to support such a state and the level of water-resource development that will be allowed is known as Classification and is comprised of seven steps (Figure 11) (Dollar *et al.*, 2010; King and Pienaar, 2011).

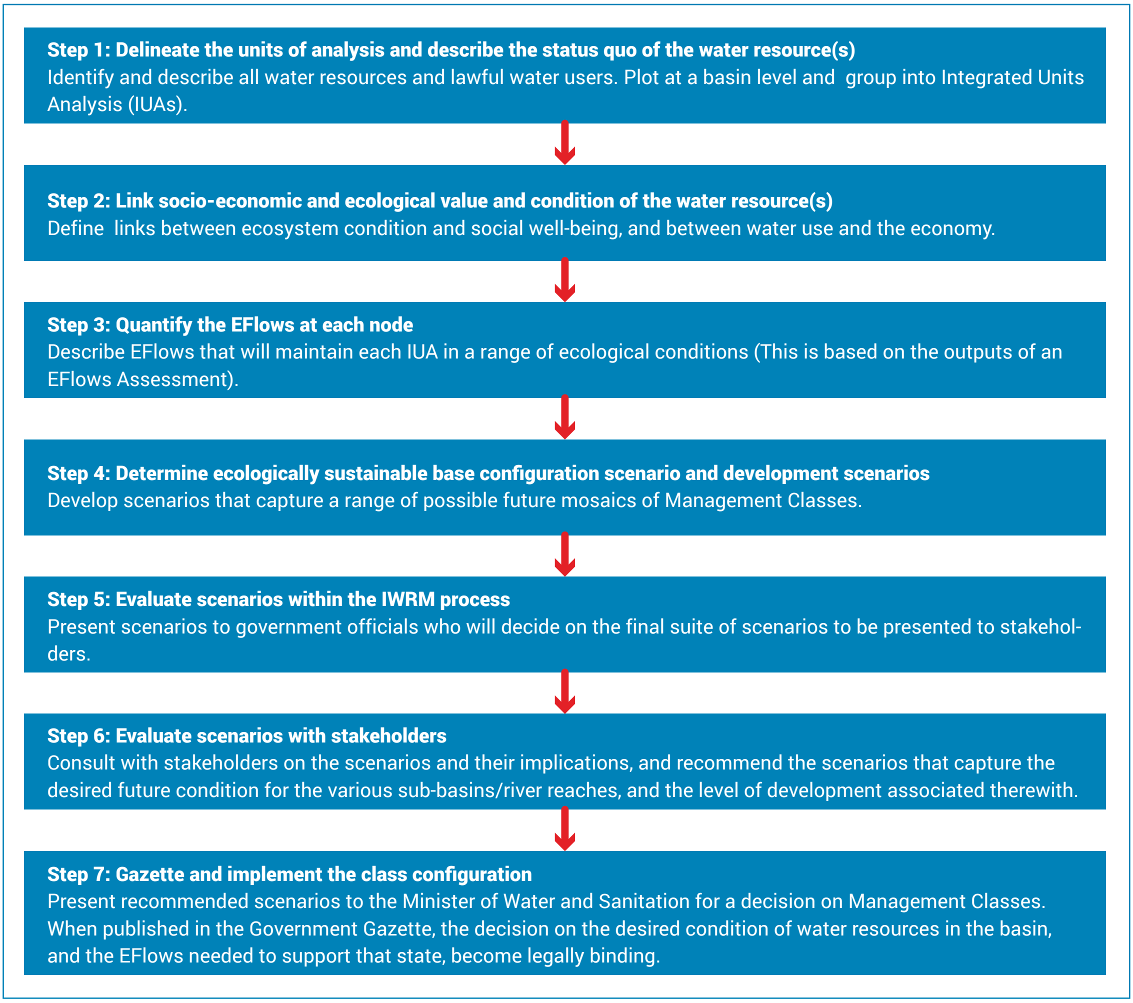
Table 14. Sustainable use of rivers: key attributes of EFlows implementation (after King and Brown, 2009a).

NO.	ATTRIBUTE
1	Development of appropriate policy, legislation and basin agreements
2	Structured and continual engagement with stakeholders
3	EFlows Assessments for river basins
4	Re-organization of institutions to meet new laws
5	Development of new kinds of licensing, infrastructure and operating rules to deliver and monitor EFlows
6	Development of regional regulatory mechanisms for licensing or re-licensing
7	Creation of awareness among governments and other stakeholders
8	Continual investment in research and capacity building
9	Delivery of the EFlows
10	Monitoring and adaptive management

6.2 Harmonizing policies and working with government agencies

Selection of an EFlows regime has implications for national/regional government agencies that deal with water, human health and well-being, agriculture, energy, mining, fisheries, coastal development and tourism, and all relevant ones should be involved in choosing the desired scenario (future). Poor synchronization of policies and confusing governance arrangements are major stumbling blocks for both the selection and implementation of EFlows. This may be because multiple government departments are involved in the management of rivers, estuaries and nearshore marine environments with poor co-operative governance. South Africa divides the management of freshwater and marine resources, for instance, leading to very good legislation for an "Ecological Reserve" for river ecosystems but none for marine ecosystems (Taljaard *et al.*, 2008).

Coordinating the process of scenario selection helps different government departments to become familiar with the concept and assessment of EFlows, the information produced by these and how implementation could proceed. One CEO of a River Basin Organization said that involvement in such work 'transformed the way he viewed rivers' and a Minister of the Environment said he had never understood until then the full implications of the decisions he makes (J. King pers. comm.).



Step 1: Delineate the units of analysis and describe the status quo of the water resource(s)
Identify and describe all water resources and lawful water users. Plot at a basin level and group into Integrated Units Analysis (IUAs).

Step 2: Link socio-economic and ecological value and condition of the water resource(s)
Define links between ecosystem condition and social well-being, and between water use and the economy.

Step 3: Quantify the EFlows at each node
Describe EFlows that will maintain each IUA in a range of ecological conditions (This is based on the outputs of an EFlows Assessment).

Step 4: Determine ecologically sustainable base configuration scenario and development scenarios
Develop scenarios that capture a range of possible future mosaics of Management Classes.

Step 5: Evaluate scenarios within the IWRM process
Present scenarios to government officials who will decide on the final suite of scenarios to be presented to stakeholders.

Step 6: Evaluate scenarios with stakeholders
Consult with stakeholders on the scenarios and their implications, and recommend the scenarios that capture the desired future condition for the various sub-basins/river reaches, and the level of development associated therewith.

Step 7: Gazette and implement the class configuration
Present recommended scenarios to the Minister of Water and Sanitation for a decision on Management Classes. When published in the Government Gazette, the decision on the desired condition of water resources in the basin, and the EFlows needed to support that state, become legally binding.

Figure 11. The steps in the South African Water Resource Classification Process (Dollar *et al.*, 2010).

In the absence of wholesale institutional reform, it may be possible to overcome governance barriers by actively encouraging coordination and cooperation between organizations (both public and private) tasked with using, developing and/or managing aquatic ecosystems. EFlows policies and procedures could also be introduced and/or synchronized in cross-cutting issues such as water-resource planning, legal challenges, social reform and climate change initiatives (Le Quesne *et al.*, 2010).

6.3 Building managerial and technical capacity in EFlows Assessment

There is a need to build managerial and technical capacity in EFlows in the WIO region, which can be enhanced through training workshops or seminars focusing on, for instance:

- the use of EFlows in decision-making for sustainable management, aimed at providing a general understanding of EFlows Assessments to professionals who need to deal with the EFlows outputs;
- technical aspects of applying the various EFlows Assessment methods for suitably-qualified professionals to develop an understanding of managerial and technical details;
- in-depth training on the facilitation of an EFlows Assessment using selected methods; and
- specialist workshops on the provision of specialist information for EFlows Assessments using selected methods.

The true understanding of the managerial and technical aspects of an EFlows Assessment, however, comes from working step by step through the process with an EFlows team, either as a coordinator, a specialist, a stakeholder, a manager or a decision maker under the guidance of an experienced EFlows practitioner. EFlows Assessments offer opportunities for hands-on learning in every facet, including: preparation of hydrological data; collection and preparation of hydraulic/hydrodynamics data; and developing specialist inputs in geomorphology/sediments, water quality, botany, zoology and social sciences. Depending on the level of experience and expertise in a particular area, professionals can either be guided by the EFlows practitioner or can be paired (and mentored by) another specialist in the same discipline who has EFlows experience. The regional EFlows champions (see introduction to Section 6) should be mentored in the EFlows Practitioner role, with a view to them taking charge of subsequent assessments. It takes repeated exposure to understand the complex linkages and the ripple effects that flow modifications have from source to sea on associated benefits and services, but this exposure and experience can be gained while taking charge of the process.

6.4 EFlows information systems

The information needed for a detailed EFlows Assessment has been described in earlier sections of this document. Important inputs are:

- a list of stakeholders and their profiles;
- a data sharing protocol;
- the relevant GIS layers, delineation of the basin and site selection;
- the ecological condition of the various river reaches and estuaries;
- a hydrological and sediment time-series for EFlow sites/locations;
- the hydraulic relationships and models constructed for EFlow sites;
- lists of indicators and links;
- a specialist, data and report for each discipline;
- the EFlows Assessment Report, which provides the outcomes of the assessment;
- the worksheets or models generated in the EFlows Assessment and user manuals, where available;
- training course materials; and
- presentations and awareness publications.

Other components of the EFlows information system can be added later and may include:

- the decision making process and details of the EFlows selected for each location;
- the EFlows Management Plan (WBG, 2017), which could include:
    - ¤ summary of the details of the basin, the EFlows team, EFlows Assessment method, dates, funder, etc.
    - ¤ record of decision and chosen EFlows

    outputs
  - a programme for monitoring compliance with, and efficacy of, chosen EFlows models/outputs
  - a framework for implementation, including the organizational capacity and competency requirements and institutional arrangements
  - reporting, record keeping and auditing/quality control arrangements
  - provisions for adaptive management
  - funding arrangements
- licensing and other use data;
- monitoring data on whether a designated EFlows is being achieved and its efficacy in maintaining the desired ecological condition;
- detailed research on one or more aspects of the aquatic ecosystems and their response to water quality and/or the flow of water, sediment and biota;
- updated data sets for hydrology, water quality or sediment;
- updates to the EFlows model based on monitoring /research data;
- decision-support systems for planning and management (Box 7); and
- calibration of meta-analysis EFlows method.

Use and sharing of an EFlows information system is greatly enhanced by formal data sharing protocol(s) (Box 7), which should aim to encompass all data and information needed to inform general decision making, planning, management, utilization, development, protection and conservation of river basins. It is, however, important that these protocols recognize and make provision for sharing data that are needed for EFlows Assessment and implementation.

6.5 Funding to support EFlows

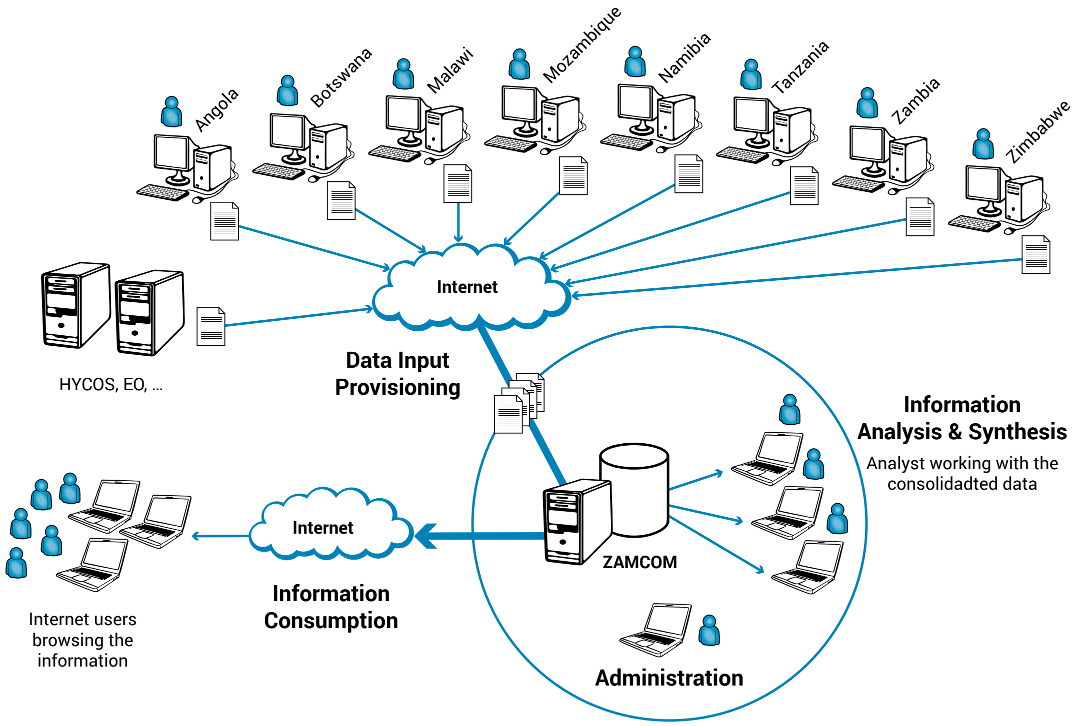
EFlows programmes, like any other government programme, require sustainable funding. Revenue sources may range from general taxes, to licence fees, hydropower compensation funds and water sales (Le Quesne *et al.*, 2010). While much of the initial funding for EFlows may come from international donors and lenders (Brown *et al.*, 2020), allocation of national funds to support the EFlows process illustrates government commitment to the principles of sustainable development and recognition of the values and ecosystem services provided by aquatic ecosystems. This in and of itself can provide much of the impetus needed to mainstream EFlows. In South Africa, the bulk of the funding for EFlows Assessment and implementation comes from the Department of Water and Sanitation. EFlows research and development is supported by the Water Research Commission via a levy on bulk sales of water to Water Boards and government irrigation schemes (King and Pienaar, 2011).

Plate 9. Fisherman on the Lower Zambezi River are highly dependent on the health and conditon of the ecosystem.

Box 7. The Zambezi Water Resources Information System (ZAMWIS)

The Zambezi Water Resources Information System (ZAMWIS) supports water-resource decision-making and planning processes in the Zambezi Basin. It comprises a core platform and database consisting of a spatial portal comprising GIS and earth observation data, primarily on hydrology. The ZAMWIS integrates data and information needed to inform general decision making, planning, management, utilization, development, protection and conservation of the Zambezi Watercourse for the benefit of human and economic development in the basin. Information on EFlows is a key component of the ZAMWIS as it provides the link between water-resource developments and riverine ecosystem health and functioning needed to inform the protection and conservation of the river ecosystem (Plate 9). EFlows in the ZAMWIS include consideration of the flow of water and sediments, and are in the form of DRIFT Equations (see Table 1) generated through the meta-analysis of individual EFlows Assessments undertaken for sites along the Zambezi River (DHI, 2017).

ZAMWIS is supported by a Data-sharing Protocol (ZAMCOM, 2016). A Windows version of ZAMWIS is installed at ZAMCOM and in the National Focus Institutions on the eight Member States. Publically-shared data will be made available through web-based versions of ZAMWIS.



7. References

Adams, J.B. 2013. A review of methods and frameworks used to determine the environmental water requirements of estuaries. Hydrological Sciences Journal 59 (3): 1-15. DOI: 10.1080/02626667.2013.816426.

Adams, J.B., Bate, G.C., Harrison, T.D., Huizinga, P., Taljaard, S., Van Niekerk, L., Plumstead, E.E., Whitfield, A.K. and Wooldridge, T.H. 2002. A method to assess the freshwater inflow requirements of estuaries and application to the Mtata Estuary, South Africa. Estuaries 25 (6B): 1382-1393.

Agostinho, A.A., Marques, E.E., Agostinho, C.S., de Almeida, D.A., de Oliveira, R.J. and de Melo, J.R.B. 2007. Fish ladder of Lajeado Dam: migrations on one–way routes? Neotropical Ichthyology 5(2). On-line version ISSN 1982-0224.

AfriDev. 2000. *The First Phase of a Cumulative Environmental Impact Assessment for the Inkomati River Basin. Unpublished Report to the Tripartite Permanent Technical Committee (TPTC) of Moçambique, Swaziland and South Africa.* Hennessy, J., King, J. and Tomlinson, J. (eds.) 75 pp. + 13 appendices, DANIDA, Copenhagen.Angelier, E. 2003. *Ecology of Streams and* Rivers. Science Publishers, Inc., Enfield. 215 pp.

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. Estuaries 25: 1246-1261.

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.

Arthington, A.H. 2012. Environmental Flows: Saving Rivers in the Third Millennium. University of California Press Freshwater Ecology Series. 424 pp. ISBN: 9780520273696.

Berry, P.F., Hanekom, P., Joubert, C., Joubert, F., Schleyer, M.H., Smale, M. and van der Elst, R. 1979. Preliminary account of the biomass and major energy pathways through a Natal nearshore reef community. South African Journal of Science 75: 565.

Berry, P.F. and Schleyer, M.H. 1983. The brown mussel *Perna perna* on the Natal coast, South Africa: utilization of available food and energy budget. Marine Ecology Progress Series 13: 201-210.

Binet, D., Le Reste, L. and Diouf, P.S. 1995. The influence of runoff and fluvial outflow on the ecosystems and living resources of West African coastal waters. In: Effects of riverine inputs on coastal ecosystems and fisheries resources. FAO Fisheries Technical Paper. 349. FAO, Rome. 133 pp.

Brown, C.A., Joubert A.R., Beuster, H., Greyling, A. and King, J.M. 2013. DRIFT: DSS software development for Integrated Flow Assessments. Final Report to the Water Research Commission. WRC project No.: K5/1873. 176 pp.

Brown, C.A. and King, J.M. 2002. Environmental flows: requirements and assessment. Chapter 3. In: Water resources management in southern Africa: enhancing environmental sustainability. A SADC/IMERCSA/IUCN Publication. 25 pp.

Brown, C., Campher, D. and King, J. 2020. Status and trends in EFlows in southern Africa. Natural Resources Forum 44:66–88. https://doi.org/10.1111/1477-8947.12190.

Bunn, S. and Arthington, A. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. Environmental Management 30(4): 492–507.

Caddy, J.F. and Bakun, A. 1995. Marine catchment basins and anthropogenic effects on coastal fishery ecosystems. In: Effects of riverine inputs on coastal ecosystems and fisheries resources. FAO Fisheries Technical Paper 349. FAO, Rome. 133 pp.

Carter, R. and Schleyer, M.H. 1988. Plankton distributions in Natal coastal waters. In: Schumann, E.H. (ed.) Coastal Ocean Studies off Natal, South Africa. Lecture notes on Coastal and Estuarine studie 26. Springer-Verlag, NY, 131-151.

Chen, H., Ma L., Guo W., Yang Y., Guo T. and Feng, C. 2013. Linking Water Quality and Quantity in Environmental Flow Assessment in Deteriorated Ecosystems: A Food Web

View. PLoS ONE 8(7): e70537. doi:10.1371/journal.pone.0070537.

Clark, B.M. and Turpie, J.K. 2014. Analysis of alternatives for the rehabilitation of the Lake St Lucia estuarine system. Anchor Environmental Consultants Report no. AEC/1487/6 submitted to iSimangaliso Wetland Park Authority.

Coastal Resources Center. 2008. "How much water do we need for nature, livelihoods and people? Assessing the environmental flow of the Wami River and its sub-basin". University of Rhode Island and Florida International University. 34 pp.

Dai, A. and Trenberth, K.E. 2002. Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. J. Hydrometeorol. 3: 660-687.

Datry, T., Singer, G., Sauquet, E., Jorda-Capdevila, D., Von Schiller, D., Stubbington, R., Magand, C., Paril, P., Miliša, M., Acuña, V., Helena Alves, M., Augeard, B., Brunke, M., Cid, N., Csabai, Z., England, J., Froebrich, J., Koundouri, P., Lamouroux, N., Martí, E., Morais, M., Munné, A., Mutz, M., Pesic, V., Previšic, A., Reynaud, A., Robinson, C., Sadler, J., Skoulikidis, N., Terrier, B., Tockner, K., Vesely, D. and Zoppini, A. 2017. Science and Management of Intermittent Rivers and Ephemeral Streams (SMIRES). Research Ideas and Outcomes 3: e21774. 23 pp.

Demetriades, N.T., Forbes, A.T., Mwanyama, N. and Quinn, N.E. 2000. Damming the Thukela River – Impacts on the Thukela Bank shallow water prawn resource. Report for Department of Water Affairs and Forestry's Thukela Water programme. Pretoria, South Africa.

Department of Water Affairs and Forestry (DWAF). 2004. Thukela Bank: Impacts of Flow Scenarios on Prawn and Fish Catch Report – Reserve Determination Study – Thukela River System. DWAF Report No. PBV000-00-10310. http://www.dwaf.gov.za/RDM/higherConfidence.asp. Pretoria, South Africa.

Department of Water Affairs and Forestry (DWAF). 2008. Water resource protection and assessment policy implementation process. Resource directed measures for protection of water resource: Methodology for the determination of the ecological water requirements for estuaries. Version 2.1. Department of Water Affairs, Pretoria, South Africa.

Department of Water Affairs and Forestry (DWAF). 2010. Feasibility Study into the Potential Development of Further Surface Water Supply Schemes for the Western Cape: Comprehensive assessment of the Ecological Water Requirements for the Berg River Estuary. Pretoria, South Africa.

DHI. 2017. Zambezi Water Resource Information System (ZAMWIS) Enhancement 3: Hydrometeorological Database and Decision Support System. Inception Report – Final Draft. ZAMCOM Secretariat. 113 pp.

Doering, P.H., Chamberlain, R.H. and Haunert, D.E. 2002. Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee Estuary. Estuaries 25: 1343-1354.

Dollar, E.S.J., Nicolson, C.R., Brown, C.A., Turpie, J.K., Joubert, A.R, Turton, A.R., Grobler, D.F. and Manyaka, S.M. 2010. The development of the South African Water Resource Classification System (WRCS): a tool towards the sustainable, equitable and efficient use of water resources in a developing country. Water Policy 12: 479–499.

Dugan, P., Barlow, C., Agostinho, A.A. and Winemiller, K.O. 2010. Fish Migration, Dams and Loss of Ecosystem Services in the Mekong Basin. AMBIO: Journal of the Human Environment 39(4): 344-348.

Dzwairo, B., Otieno, F. and Ochieng, G. 2010. Making a case for systems thinking approach to integrated water resources management (IWRM). International Journal of Water Resources and Environmental Engineering 1: 107–113.

Flannery, M.S., Peebles, E. and Montgomery, R.T., 2002. A percent-of-flow approach for managing reductions of freshwater inlows from unimpounded rivers to Southwest Florida Estuaries. Estuaries 25: 1318-1332.

Feely, R.A., Alin, S.A., Newton, J., Sabine, C.L., Warner, M., Devol, M., Krembs, C. and Maloy, C. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. Estuarine, Coastal and Shelf Science 88: 442-449.

Gammelsrød T. 1992. Variation in shrimp abundance on the Sofala Bank, Mozambique, and its relation to the Zambezi River runoff. Estuarine, Coastal and Shelf Science 35: 91–103. doi: 10.1016/S0272-7714(05)80058-7.

Gippel, C. J. and Stewardson, M.J. 1998. Use of wetter perimeter in defining minimum environmental flows. Regulated Rivers: Research and Management 14: 53-67.

Gillanders, B.M. and Kingsford, M.J. 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.

Global Water Partnership-Technical Advisory Committee (GWP-TAC). 2000. Integrated Water Resources Management. TAC background Papers 4: Stockholm, Sweden. 71 pp. ISBN: 91-630-9229-8.

Global Water for Sustainability Programme – Florida International University (GLOWS – FIU). 2014. Wami River Basin, Tanzania, Environmental Flow Assessment Phase II 66 pp. ISBN-13: 978-1-941993-00-2.

Godfrey, L. (ed). 2002. Ecological Reserve Determination for the Crocodile River Catchment, Incomati System, Mpumalanga. Technical Report for the Department of Water Affairs and Forestry, by the Division of Water Environment and Forestry Technology, CSIR, Pretoria. Report No. ENV-P-C 2001.

Halliday, I.A. and Robins, J.B. 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.

Harris, R.J., Milbrandt, E.C., Brovard, B. and Everham, E. 2010. The effects of reduced tidal flushing on mangrove structure and function across a disturbance gradient. Estuar. Coasts 33: 1176–1185.

Harwood, A.J., Tickner, D., Richter, B., Locke, A., Johnson, S. and Xuezhong, Y. 2018. Critical factors in water policy to enable Environmental Flow implementation. 30 May 2018. DOI: 10.3389/fervs.2018.00037. 7 pp.

Hughes, D.A., Desai, A.Y., Birkhead, A.L. and Louw, D. 2013. A new approach to rapid, desktop level, environmental flow assessments for rivers in southern Africa. Hydrological Sciences Journal 59(3-4): 673-687.

Hughes, D. and Hannart, P. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. Journal of Hydrology 270: 167-181.

Hughes, D. and Louw, D. 2010. Integrating hydrology, hydraulics and ecological response into a flexible approach to the determination of environmental water requirements for rivers. Environmental Modelling and Software 25(8): 910-918.

Hughes, D.A. and Münster, F. 2000. Hydrological information and techniques support the determination of the water quality component of the ecological reserve for rivers. Water Research Commission Report NTT 137/00. Pretoria, South Africa. 91 pp.

International Centre for Environmental Management (ICEM) 2010. MRC Strategic Environmental Assessment (SEA) of hydropower on the Mekong mainstream: summary of the final report. Hanoi, Viet Nam.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge., UK.

Jassby, A.D., Kimmerer, W.J., Monismith, S.G., Armor, C., Cloern, J.E., Powel, T.M., Schubel, J.R. and Vendlinski, T.J. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecological Applications 5: 272–289.

Jorde, K. 1999. Das Simulationsmodell CASIMIR als Hilfsmittel zur Festlegung ökologisch begründeter Mindestwasserregelungen, Tagungsband Problemkreis Pflichtwasserabgabe, 21-23. Juni 99, Graz, Schriftenreihe Euronatur.

Jowett, I.G. 1997. Instream flow methods: a comparison of approaches. Regulated Rivers: Research and Management 13: 115-127.

King, J.M. and Brown, C.A. 2009a. Integrated

Flow Assessments: concepts and method development in Africa and South-east Asia. Freshwater Biology 55 (1): 127-146.

King, C.A. and Brown, C.A. 2009b. Environment protection and sustainable management of the Okavango River Basin: Preliminary Environmental Flows Assessment. Scenario Report: Ecological and social predictions. Project No. UNTS/RAF/010/GEF. Report No. 07/2009.

King, J.M. and Brown, C.A. 2018. Environmental Flows, minimum flows and the mystery of ten percent. p. 107-111. In: Gough, P. and Royte, J. (eds.) Sea to Source. Protection and restoration of fish migration in rivers worldwide. World Fish Migration Foundation.

King, J., Beuster, H., Brown, C. and Joubert, A. 2014. Pro-active management: the role of environmental flows in transboundary cooperative planning for the Okavango River system. Hydrological Sciences Journal DOI: 10.1080/02626667.2014.888069.

King, J.M. and Louw, D. 1998. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. Aquatic Ecosystems Health and Restoration 1: 109-124.

King, J. and Pienaar, H. 2011. Sustainable use of South Africa's inland waters. Pretoria: Water Research Commission, Pretoria. Water Research Commission, Pretoria. ISBN 978-1-4312-0129-7. 259 pp.

Kleynhans, C.J. 1996. A qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River. Journal of Aquatic Ecosystem Health 5: 41-54.

Lake Victoria Basin Commission (LVBC) and WWF Eastern & Southern Africa Regional Programme Office (WWF-ESARPO). 2010. Assessing Reserve Flows for the Mara River. Nairobi and Kisumu, Kenya. 60 pp.

Lamberth, S.J., Drapeau, L. and Branch, G.M. 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.

Linnansaari, T., Monk, W.A., Baird, D. and Curry, R.A. 2013. Review of approaches and methods to assess Environmental Flows across Canada and internationally. Canadian Science Advisory Secretariat. Research Document 2012/039. ISSN 1919-5044. 82 pp.

Lloyd, L.N., Anderson, B.G., Cooling, M., Gippel, C.J., Pope, A.J. and Sherwood, J.E. 2012. Estuary Environmental Flows Assessment Methodology for Victoria. Lloyd Environmental Pty Ltd Report to the Department of Sustainability and Environment, Melbourne Water and Corangamite CMA, Colac, Victoria, Australia.

Louw, D. (ed.) 2007. Joint Maputo River Basin Resources Study: Intermediate Environmental Flow Requirements Assessment Task Report. 6.1(b2)/2007. (EuropeAid/120802/D/SV/ZA). Joint Maputo River Basin Water Resources Study, Moçambique, Swaziland And South Africa by Plancenter and Associates.

Louw, D. and Koekemoer, S. (eds.) 2007. Joint Maputo River Basin Resources Study: Intermediate EcoClassification of four EFR sites. 6.1(b1)/2007. (EuropeAid/120802/D/SV/ZA). Joint Maputo River Basin Water Resources Study, Moçambique, Swaziland And South Africa by Plancenter and Associates.

Le Quesne, T., Kendy, E. and Weston, D. 2010. The implementation challenge: taking stock of government policies to protect and restore environmental flows. WWF and Nature Conservancy. 68 pp.

Mann, K.H. and Lazier, J.R.N. 2013. Dynamics of marine ecosystems – biological-physical interactions in the oceans. Boston: Blackwell Scientific Publications.

Mattson, R.A. 2002. A resource-based framework for establishing freshwater inflow requirements for the Suwannee River Estuary. Estuaries 25: 1333-1342.

McClain, M., Tharme, R., O'Keeffe, J., Kasanga, W., Corzo, G., Crosato, A., et al. (2016). Environmental Flows in the Rufiji River Basin assessed from the perspective of planned developments in the Kilombero and Lower Rufiji Sub-Basins. Report published by USAID.

McNally, W.H. and Mehta, A.J. 2004. Sediment Transport in Estuaries. In: Isla, F.I. (ed.) Coastal Zones and Estuaries. Encyclopaedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Paris, France, [http://www.eolss.net]. 9 pp.

Meybeck, M. and Helmer, R. 1996. An Introduction to Water quality. In: Chapman, D. (ed.) Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring Second Edition. UNESCO/WHO/UNEP. ISBN 0 419 21590 5 (HB) 0 419 21600 6 (PB).

MEA (Millenium Ecosystem Assessment). 2005. Ecosystems and Human Well-Being: Synthesis. Washington, DC: Island Press.

Mekong River Commission (MRC). 2017. The Council Study: Study on the sustainable management and development of the Mekong River, including impacts of mainstream hydropower projects. BioRA Final Technical Report Series. Volume 4: Assessment of Planned Development Scenarios. FINAL REPORT. Vientiane, Lao PDR. 145 pp.

Montagna, P.A., Hill, E.M. and Moulton, B. 2009. Role of science-based and adaptive management in allocating environmental flows to the Nueces Estuary, Texas, USA. WIT Transactions on Ecology and the Environment 122: 559-570.

Monteiro, P.M.S. and Marchand, M. 2007. A system approach to coupled rivers – coastal ecosystem science and management. Catchment2Coast Executive Summary. 14 pp.

Monteiro, P. and Matthews, S. 2003. Catchment2Coast: Making the link between coastal resource variability and river inputs. South African Journal or Science 99: 299-301.

Mouyen, M., Longuevergne, L., Steer, P., Crave, A., Lemoine, J-M., Save, H and Robin, C. 2018. Assessing modern river sediment discharge to the ocean using satellite gravimetry. Nature Communications 9(3384).

Nunn, A.D. and Cowx, I.G. 2012. Restoring River Connectivity: Prioritizing Passage Improvements for Diadromous Fishes and Lampreys. AMBIO: Journal of the Human Environment 41(4): 402–409.

OKACOM. 2011. The Permanent Okavango River Basin Water Commission: Cubango-Okavango River Basin Transboundary Diagnostic Analysis. Maun, Botswana: OKACOM.

O'Keeffe, J.H. 2018. A Perspective on Training Methods Aimed at Building Local Capacity for the Assessment and Implementation of Environmental Flows in Rivers. Front. Environ. Sci., 23 October 2018 https://doi.org/10.3389/fenvs.2018.00125.

O'Keeffe, J., Graas, S., Mombo, F. and McClain, M. 2017. Stakeholder-Enhanced Environmental Flow Assessment: The Rufiji Basin Case Study in Tanzania. River Research & Applications 27 September 2017 https://doi.org/10.1002/rra.3219.

O'Keeffe, J., Hughes, D.A. and Tharme, R. 2002. Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method. Verh. Internat. Verein. Limnol. 28: 84-92.

Overton, I., Smith, D., Dalton, J., Barchiesi, S., Acreman, M., Stromberg, J., et al. 2014. Implementing environmental flows in integrated water resources management and the ecosystem approach. Hydrological Science Journal: 860-877.

Paterson, A., Lindsay, J., and Pereira, M. 2008 Joint Maputo River Basin Resources Study. Scoping Report – Long Term Implications of Freshwater Abstraction on the Maputo Estuary and Bay. EuropeAid/120802/D/SV/ZA. Joint Maputo River Basin Water Resources Study, Moçambique, Swaziland and South Africa by Plancenter and Associates.

Pegram, G., Li, Y., Le Quesne, T., Speed, R., Li, J. and Shen, F. 2013. River basin planning: Principles, procedures and approaches for strategic basin planning. UNESCO. Paris.

Peirson, W.L., Bishop, K., Van Senden, D., Horton, P.R. and Adamantidis, C.A. 2002. Environmental Water Requirements to maintain Estuarine Processes. Environmental Flows Initiative Technical Report Number 3. Commonwealth of Australia. Canberra. 158 pp. www.environment.gov.au/water/publications/environmental/rivers/nrhp/pubs/estuarine.pdf Accessed on October 19, 2012.

Peters, N.E. and Meybeck, M. 2009. Water Quality Degradation Effects on Freshwater Availability: Impacts of Human Activities. Journal Water International 25(2).

Petersen, C.R., Jovanovic, N.Z., Le Maitre, D.C. and Grenfell, M.C. 2017. Effects of land use change on streamflow and stream water quality of a coastal catchment. Water SA 43(1):

139-152.

Poff, N.L., Allan, J.D., Bain, M. B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. 1997. The natural flow regime. BioScience 47: 769–784.

Poff, N.L. and 17 others. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental standards. Freshwater Biology 55: 147-170.

Porter, S. 2009. Biogeography and potential factors regulating shallow subtidal reef communities in the western Indian Ocean. PhD thesis, University of Cape Town, South Africa.

PWBO/IUCN. 2007. Estuary Health Assessment for Pangani River Basin. Unpublished technical report. Pangani Water Basin Office, Moshi and IUCN Eastern Africa Regional; Programme. 123 pp.

PBWO/IUCN. 2009. Final Scenario Report: Report 4: Pangani River Basin Flow Assessment, Moshi, 23 pp.

Quiñones, R.A. and Montes, R.M. 2001. Relationship between freshwater input to the coastal zone and the historical landing of the benthic/demersal fish Eleginops maclovinus in central-south Chile. Fisheries Oceanography 10: 311-328.

Reinecke, M.K., Brown, C.A., Esler, K.J., King, J.M., Kleynhans, M.T. and Kidd, M. 2014. Links between lateral vegetation zones and river flow. Wetlands DOI 10.1007/s13157-015-0634-6. 16 pp.

Reinecke, M.K., Brown, C.A., Esler, K.J., King, J.M., Kleynhans, M.T. and Kidd, M. 2014. Links between lateral vegetation zones and river flow. Wetlands DOI 10.1007/s13157-015-0634-6. 16 pp.

Richter, B. 2009. Re-thinking environmental flows: from allocations and reserves to sustainability boundaries. Rivers Research and Application. 23 September 2009 https://doi.org/10.1002/rra.1320.

Rodríguez, J.P., Rodríguez-Clark, K.M., Baillie, J.E.M et al. 2011. Establishing IUCN Red List Criteria for Threatened Ecosystems. Conservation Biology 25: 21–29.

Seaman, M., Watson, M., Avenant, M., King, J., Joubert, A., Barker, C., Esterhuyse, S., Graham, D., Kemp, M., le Roux, P., Prucha, B., Redelinghuys, N., Rossouw, L., Rowntree, K., Sokolic, F., van Rensburg, L., van der Waal, B., van Tol, J. and Vos, T. 2016. DRIFT-ARID: A method for assessing environmental water requirements (EWRs) for non-perennial rivers. Water SA 42(3): 12 pp.

Scott, G.R. and Sloman, K.A. 2004. The effects of environmental pollutants on complex fish behaviour: integrating behavioural and physiological indicators of toxicity. Aquatic Toxicology 68(4): 369-392.

Schleyer, M.H. 1981. Microorganisms and detritus in the water column of a subtidal reef in Natal. Marine Ecology Progress Series 4: 307-320.

Smetacek, V.S. 1986. Impact of Freshwater Discharge on Production and Transfer of Materials in the Marine Environment. In: Skreslet S. (eds) The Role of Freshwater Outflow in Coastal Marine Ecosystems. NATO ASI Series (Series G: Ecological Sciences), Vol 7. Springer, Berlin, Heidelberg.

Southern Waters. 2006. Instream Flow Assessment: Metolong Dam EIA. Consultancy Report to SMEC Africa for Lesotho Water Affairs. 113 pp.

Southern Waters. 2019a. DRIFT-derived EFlows equations for ZAMWIZ. Unpublished report for ZAMCOM and DHI. 36 pp.

Southern Waters. 2019b. Batoka Hydropower Plant: Updated and expanded final report. Environmental Flow Assessment. Unpublished technical report to ERM. February 2014. 85 pp.

Stalnaker, C., Lamb, B.L., Henriksen, J., Bovee, K. and Bartholow, J. 1995. The Instream Flow Incremental Methodology: A primer for IFIM. Biological Report 29, March 1995. US Department of the Interior. National Biological Service. Washington, D.C. 46 pp.

Staples, D.J. and Vance, D.J. 1986. Emigration of juvenile banana prawns Penaeus merguiensis from a mangrove estuary and recruitment to offshore areas in the wet-dry tropics of the Gulf of Carpentaria, Australia. Marine Ecology Progress Series 27: 239-252.

SWECO International. 2005. NDF 197 First National Water Development Project: Joint Umbeluzi River Basin Study. Final Report.

Taljaard, S., Adams, J.B., Turpie, J.K., Van Niekerk, L., Demetriades, N., Bate, G.C., Cyrus, D., Huizinga, P., Lamberth, S. and Weston, B. 2008. Water Resource Protection and Assessment Policy Implementation Process. Resource Directed Measures for protection of water resources: Methodology for the Determination of the Ecological Water Requirements for Estuaries. Version 2. Department of Water Affairs and Forestry, Pretoria, South Africa.

Taljaard, S., Van Niekerk, L. and Joubert, W. 2009. Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: Southern Hemisphere perspective. Estuarine, Coastal and Shelf Science 85: 407-421.

Temane, L., Le, Q.B. and Vlek, P.L.G. 2014. A landscape planning and management tool for land and water resources management: An example application in northern Ethiopia. Water Resources Management 28(2): 407-424.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1(4): 6-10.

Tharme, R. 2003. A Global perspective on Environmental Flow Assessment. Emerging trends in the development and application of environmental flow methodologies for river. River Research and Applications 22 September 2003 https://doi.org/10.1002/rra.736: 397-441.

Tong, S., and Chen, W. 2002. Modelling the relationship between land use and surface water quality. Journal of Environmental Management 66 (2002): 377-393.

United National Environment Programme (UNEP). 2018. WIOSAP Project Summary: Implementation of the Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities (WIO-SAP). UNEP, Nairobi. 8 pp.

Van Ballegooyen, R., Taljaard, S., Van Niekerk, L. and Huizinga, P. 2004. Using 3-D modelling to predict physico-chemical responses to variation in river inflow in smaller, stratified estuaries typical of South Africa. Journal of Hydraulic Research 42: 563–577.

Van Ballegooyen, R.C., Taljaard, S., van Niekerk, L., Lamberth, S.J., Theron, A.K. and Weerts, S.P. 2007. Freshwater flow dependency in South African marine ecosystems: a proposed assessment framework and initial assessment of South African marine ecosystems. WRC Report No. KV 191/07. Pretoria: Water Research Commission.

Van Niekerk, L. and Lamberth, S.J. (eds). 2013. Estuary and Marine EFR assessment. Volume 3: Assessment of the Role of Freshwater Inflows in the Coastal Marine Ecosystem. Research project on environmental flow requirements of the Fish River and the Orange-Senqu River Mouth. UNDP-GEF Orange-Senqu Strategic Action Programme (Atlas Project ID 71598). Technical Report 34. Report for the Orange-Senqu River Basin Orange-Senqu River Commission Secretariat. Governments of Botswana, Lesotho, Namibia and South Africa http://wis.orasecom.org/content/study/UNDP-GEF/general/Documents/Techincal%20Reports/TR34_OrangeMarine%20Report_Rev0_18Nov2013.pdf.

Van Niekerk, L., Adams, J.B., Allan, D.G., Taljaard, S., Weerts, S.P., Louw, D., Talanda, C. and Van Rooyen, P. 2019. Assessing and planning future estuarine resource use: A scenario-based regional scale freshwater allocation approach. Science of the Total Environment 657(2019): 1000-1013.

Vance, D.J., Haywood, M.D.E., Heales, D.S., Kenyon, R.A. and Loneragan, N.R. 1998. Seasonal and annual variation in abundance of postlarval and juvenile banana prawns Penaeus merguiensis and environmental variation in two estuaries in tropical northeastern Australia. Marine Ecology Progress Series 163: 21-36.

Van Schoik, R., Brown, C., Lelea, E., Conner, A. 2004. Barriers and Bridges: Managing Water in the U.S.-Mexican Border Region. Environment: Science and policy for Sustainable Development 46(1): 26-41.

Warner, J. 2006. Multi-stakeholder platforms: integrating society in water resource management. Ambiente & Sociedade 8(2): 4-28.

World Bank Group (WBG). 2017. The Cubango-Okavango River Basin. Multi-Sector Investment Opportunities Analysis. Volume 2. Main Report. August 2017. 84 pp.

World Bank Group (WBG). 2018. Good Practice Handbook: EFlows Assessments for hydropower projects. World Bank Group, Washington. 135 pp.

Whitfield, A.K. 1998. Biology and ecology of fishes in southern African estuaries. J.L.B. Smith Institute of Ichthyology. Ichthyological Monograph Number 2. Grahamstown, South Africa.

Whitfield, A. and Elliot, M. 2011. Ecosystem and Biotic Classifications of Estuaries and Coasts. In: Wolanski, E. and McLusky, D.S. (eds). Treatise on Estuarine and Coastal Science 1: 99-124. Academic Press.

WRI. 2001. People and Ecosystems: The Fraying Web of Life. World Resource Series; UNDP, UNEP, World Bank, World Resources Institute. Elsevier, Oxford, UK.

ZAMCOM. 2016. Rules and procedures for sharing of data and information related to the management and development of the Zambezi Watercourse. Adopted by the ZAMCOM Council 25th February 2016. 31 pp.

The Nairobi Convention through the GEF-funded project, Implementation of the Strategic Action Programme for the protection of the Western Indian Ocean from land-based sources and activities (WIOSAP), in collaboration with WIOMSA, are facilitating the production of a series of regional guidelines. The first three volumes are on Seagrass Ecosystem Restoration, Mangrove Ecosystem Restoration and Assessment of Environmental Flows in the WIO Region.

The participating countries in the WIOSAP include Comoros, Madagascar, Mauritius, Seychelles, Mozambique, Kenya, Tanzania, France (not a beneficiary of GEF funds), Somalia and South Africa. The Goal of the WIOSAP is to: 'Improve and maintain the environmental health of the region's coastal and marine ecosystems through improved management of land-based stresses'. The specific objective of the WIOSAP is 'To reduce impacts from land-based sources and activities and sustainably manage critical coastal-riverine ecosystems through the implementation of the WIOSAP priorities with the support of partnerships at national and regional levels.'