Scoping a Ridge to Reef Approach: Impacts of the Orange-Senqu River Basin on the Benguela Current Large Marine Ecosystem

Concept Paper

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1. INTRODUCTION

The Orange-Senqu River is the third largest river basin in southern Africa. It is located within in the territories of Lesotho, South Africa, Botswana and Namibia. The Orange-Senqu drains in to the Atlantic Ocean at the border between South Africa and Namibia, where it forms a large estuarine delta. This estuarine delta (or estuary) represents a unique ecosystem on what is otherwise a wave exposed, hyper-arid coast with few freshwater inputs. The Orange-Senqu River estuary is recognised as an internationally important wetland for migratory birds and was accorded Ramsar Status in 1991 (Cowan 1995). It is the only large estuarine nursery area in the region, supporting significant populations of estuarine and marine invertebrate and fish species (Taljaard *et al.* 2003). It is ranked as the 7th most important system in South African in terms of conservation importance (Turpie *et al*. 2002). Freshwater, sediment, organic matter and nutrients discharged through the estuary mouth also make a potentially important contribution to the Benguela Current Large Marine Ecosystem (LME) that surrounds the mouth of the estuary.

Abstraction of large volumes of water from the catchment for urban, industrial and agricultural use has, however, significantly reduced natural flows within the system. Regulation of flows by some 30 large dams on the system, has also significantly altered the natural flow regime of the river. The quality of the water in the river is severely degraded by seepage, runoff and point source discharges that include municipal, industrial and agricultural effluents, and by high sediment loads resulting from land degradation in many parts of the catchment (ORASECOM 2008). These actions have degraded the estuary to the extent that it has been placed on the Monteux Record (a list of Ramsar sites around the world that are in a degraded state). A recent study commissioned by the Department of Water Affairs in South Africa and Department of Water Affairs in Namibia (Taljaard *et al.* 2003) concluded that the Present Ecological Status of the estuary was in a condition described as largely modified (D+) and was on a negative trajectory of change. The current freshwater inflow is less than 50% of the natural inflow, while the occurrence of significant floods and even elevated flows is very much reduced. Localised anthropogenic impacts such as the construction of roads, dykes, slimes dams near the mouth, have further degraded the estuary. Little is known of what impact changes in the flow regime of the Orange-Senqu River and the degradation of the estuary have had on the broader Benguela Current System.

Recognising the importance and extent of the threat to the Orange-Senqu system and adjacent marine environment, the Governments of Lesotho, South Africa, Botswana and Namibia concluded the “Agreement on the Establishment of the Orange-Senqu River Commission” in 2000 (ORASECOM Agreement) as part of their commitment to address threats to shared water resources in the region. One of the key objectives for ORASECOM, recognised by all States, was the development of a basin-wide management plan for the system. The UNDP-GEF funded project, the Orange-Senqu Transboundary Diagnostic Analysis (TDA) and Strategic Action Programme (SAP), was one of the first interventions in this respect, and aims to contribute to the development of this basin-wide plan. The preliminary TDA that was developed for this study (ORASECOM 2008), however, did not adequately consider impacts of altered flow regimes, reduced water quantity and impaired water quality of the Orange-Senqu River on the adjacent marine environment including the estuary.

This document is a concept paper that summarises the major impacts of the Orange-Senqu River on the Benguela Current LME and includes a tentative causal chain analysis of prioritized impacts. It forms the basis of a more detailed scoping report that will seek to describe and prioritise the major impacts of the Orange-Senqu River on the Benguela Current LME, to be finalised following a workshop with key stakeholders in the region.

This approach adopted for the study follows the GEF International Waters TDA approach to identifying the major impacts of the Orange-Senqu River Basin on the estuary and Benguela Current LME, with a view to understanding (and if possible quantifying) the mechanics behind these impacts, prioritising the issues and providing a tentative catalogue of 'who could do what'. The approach involves the following steps:

- Identification and initial prioritisation of transboundary problems;
- Gathering and interpreting information on environmental impacts and socio-economic consequences of each problem;
- Causal chain analysis (including root causes);
- Completion of an analysis of institutions, laws, policies and projected investments.

Information contained in this paper is based on a review of relevant scientific literature and data, and the consultant's own experience and knowledge of estuarine and marine ecology.

2. IMPACTS ON THE ECOLOGICAL FUNCTIONING AND IMPORTANCE OF THE ORANGE-SENQU ESTUARY

The ecological functioning and health of the Orange-Senqu Estuary was recently assessed by Taljaard *et al.* (2003) using methods prescribed by the South African Department of Water Affairs and Forestry (DWAF 1999), for the determination of freshwater requirements of estuaries in South Africa. This study looked at the full suite of abiotic (hydrology, hydrodynamics, sediment processes, and water quality) and biotic (microalgae, macrophytes, invertebrates, fish and birds) ecosystem components of the estuary. This study was undertaken at a desktop level (relied on available information only) but did include simulated hydrology for the entire system. Historic information available on the Orange-Senqu Estuary at the time that this study was undertaken includes that on water quality (Brown 1959, Day 1981, CSIR 1984, 1985, 1988, Harrison 1997, Seaman & van As 1998), vegetation (O'Callaghan 1984, Burns 1989, Morant & O'Callaghan 1990, Raal 1996, Anon 2002, Bornman 2002), invertebrate fauna (Brown 1959, Morant & O'Callaghan 1990), fish (Brown 1959, Day 1981, Morant & O'Callaghan 1990, Harrison 1997, Seaman & van As 1998) and birds (Ryan & Cooper 1985, Anderson *et al.* 2003). More recently, additional information has been collected on water quality (van Niekerk *et al*. 2008), vegetation (Bornman *et al*. 2004, Shaw *et al.* 2008, and Bornman & Adams 2010, van Niekerk *et al*. 2008), fish fauna (van Niekerk *et al*. 2008) and birds (van Niekerk *et al*. 2008) of the estuary

This section of the paper provides a brief account of the present ecological state of the Orange-Senqu estuary, and likely changes in the system from the natural (reference) state, based on information provided in these references and general literature on estuarine ecology and functioning.

2.1. Impacts on the abiotic characteristics of the estuary

Orange-Senqu River System is one of largest river systems in southern Africa, and is classified as one of the world's major river (i.e. has a mean annual runoff exceeding 10 km^3) (Bremner *et al*. 1990). It stretches over 2 300 km from its source to the mouth, and has a catchment exceeding one million km^2. Most of the catchment is arid to semi-arid in nature, where mean annual potential evaporation vastly exceeds mean annual precipitation. Nearly all the runoff in the catchment (98.2%) is derived from the upper portion of the catchment, above the Vaal Orange confluence (Kriel 1972, Benade 1988) (Figure 1). Enormous volumes of water are abstracted from river, mostly from the 30 or so large dams that have been constructed on the system. The Orange-Senqu system is also connected to other river systems for water import and export via six interbasin water transfer schemes (van Niekerk *et al*. 2008). One of these schemes, the Lesotho Highlands Water Project may, for example, transports approximately 2 000 million m^3 of water from the Orange River headwaters to the Vaal Dam Catchment when the scheme is fully operational. Mean annual runoff (MAR) under the present state is approximately 4 744 Million m^3, but has been reduced by almost 60% from the natural (reference) state (10 833 Mm^3). Further reductions in MAR for the system are anticipated in the future, due to the escalation in demands for water for irrigation and other uses (van Niekerk et al. 20008).

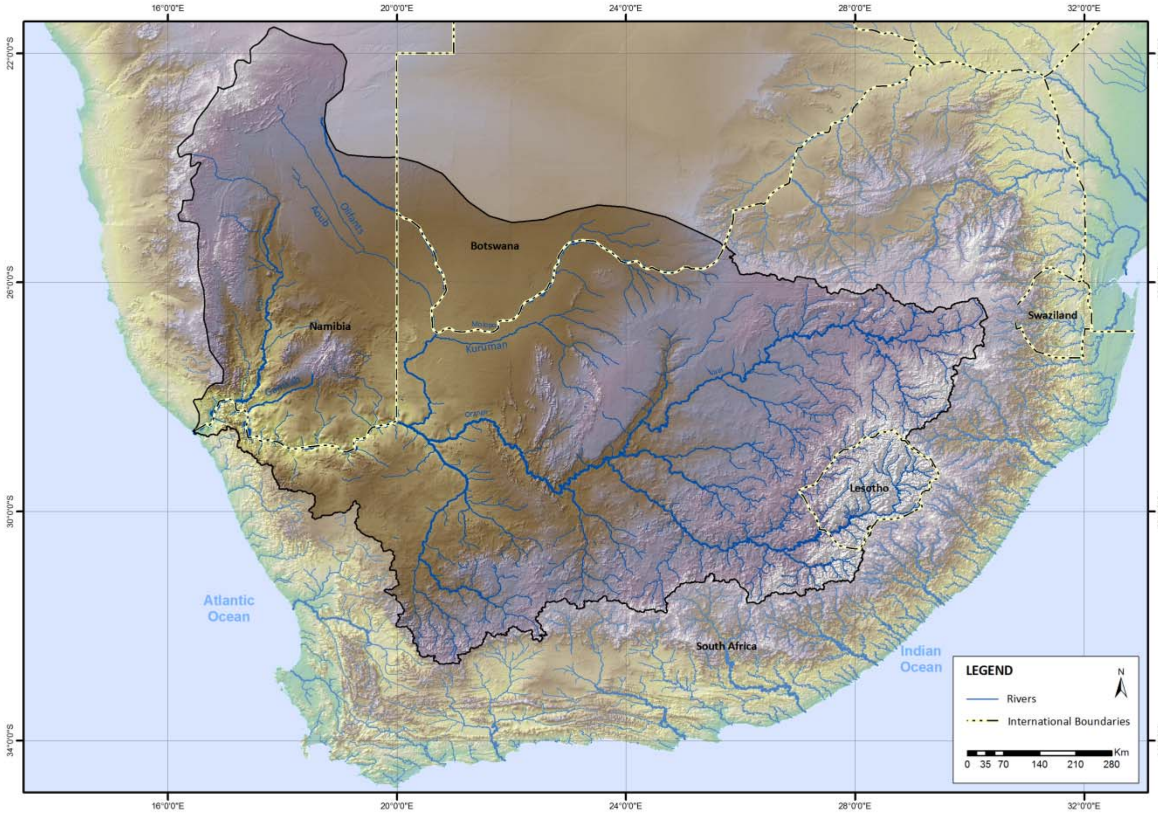

Figure 1.Extent of the Orange-Senqu catchment in southern Africa.

Historically the Orange-Senqu Estuary experienced a strong seasonal pattern of flows, with low flow or no-flow conditions generally coinciding with dry periods in the catchment in winter (August-September), while the system was flushed by small to severe floods during the summer season (Brown 1959, Williams 1990, Taljaard *et al.* 2003). However, abstraction of water from the river, flow regulation and aseasonal releases by the major dams in the catchment has diminished the flow pattern to the extent that no discernable flood season has been experienced in years (Taljaard *et al.* 2003). The highest average monthly flows have been reduced by almost 30% in the Present state relative to the Reference condition, while the incidence of actual flood events (those with a return period greater 1: 5 years) have been reduced by almost 50% (from an estimated 16 events that would have been recorded under reference conditions to only 9 recorded in the Present state) (Taljaard *et al.* 2003).

Floods are important for the long-term functioning of estuaries. Small floods play an important role in influencing the channel configuration, while large floods scour out tidal deltas and re-set the mouth conditions (Schumann *et al.* 1999). Under the current flow regime, whereby a more controlled and constant flow reaches the estuary, with major dams absorbing most of the smaller floods and buffering the effects of medium floods, only severe floods can effectively flush the system (Williams 1990, Bornman & Adams 2010). These floods play an important role in estuaries in that they erode accumulated sediment, temporarily deepening the channel in such systems and thus prolonging the period for which the mouth of the estuary remains open (Cooper *et al*. 1999). Back floods, resulting from the build-up of water levels in the estuary during periods when the estuary mouth is closured, are also essential to estuarine health. Due to the sustained release of water from dams during winter and the artificial control of the mouth, the state of the estuary mouth has changed from one that closed periodically to one that now remains permanently open thereby preventing back flooding (Bornman & Adams 2010). The mouth of the Orange-Senqu used to close approximately once every four years on average during periods of low river flow, before the commissioning of the major dams on the river (Taljaard *et al.* 2003). On occasions when the mouth has closed in recent decades, it has often been breached either by the diamond mining concession holders on either side of the river (Namdeb and Alexcor) in an effort to protect low-lying infrastructure from being flooded. These alterations to the flow regime and artificial breaching events have contributed to the deterioration of the internationally significant wetland habitat in the estuary (more on this in the section on estuarine biota below).

A number of other anthropogenic flood control measures at the mouth have also contributed to a reduction in inundation of salt marsh surrounding the estuary. A causeway was constructed through the salt marsh to provide easy access to the beach from Alexander Bay, on the south side of the estuary. This causeway stands about 1.5 m above the adjacent salt marsh (CSIR 1991), and has effectively cut off of many of the river channels extending through the southern edge of the marsh, and ultimately has contributed to the destruction of this saltmarsh (Taljaard *et al.* 2003). A number of dykes were also constructed across the flood channels extending down into the marsh starting in 1974 in an effort to protect Alexkor agricultural land on the southern side of the mouth from flooding (CSIR 1991). These dykes have also served to reduce the penetration of flood water into the salt marsh on this side of the mouth. Dykes were also constructed by Namdeb on the north bank in 1974, to protect the golf course from flooding (CSIR 1991). The dykes on both banks constrict flow during floods, leading to local increases in river flow velocity and increased erosion along bends in the river course (Taljaard *et al.* 2003). Alexkor have constructed a slimes dam to the east of the salt marsh. Fine material (from the slimes dam and other mining activities in the area) is transported by wind into the salt marsh. Seepage of saline water from the dam into the adjacent salt marsh has resulted in localised incidence of hypersalinity (CSIR 1991). These effects together have also contributed to the die-back of marsh vegetation surrounding the mouth of the estuary.

Despite the large reductions flow including flood frequency and intensity, the estuary morphology and depth is reportedly relatively similar to its natural state (Taljaard *et al.* 2003). Although major impoundments trap much sediment and reductions in flow velocity and volume have reduced the sediment carrying capacity of the system, river sediment still dominates over that from the sea in the estuary. It is reasoned that the loss of sediment inputs from the upper catchment are balanced by enhanced inputs resulting from increased erosion in the mid and lower catchment. Variability in morphology and sediment processes in the estuary are probably somewhat reduced though, due to the reduced resetting of the estuary by floods, while the intrusion of marine sediments into the estuary has most likely extended slightly further up the estuary (Taljaard *et al.* 2003). Sand banks in the estuary are likely to be more permanently exposed in the Present state, and as a consequence have become vegetated. Further discussion on the export of sediment to the marine is included in the section addressing impacts on the marine environment.

Water quality data available for the Orange-Senqu Estuary indicate that it exhibits strong seasonal variation with winter temperature being typically lower (around 15 ^{0}C) than summer temperatures (around 25 ^{0}C) except during periods of intense upwelling when cool water (12-16^{0}C) from the sea enters the estuary. Oxygen levels in the estuary are mostly high (around 8 mg/l) except on occasions when algal blooms occur in dams upstream, and this deoxygenated water makes its way down into the estuary (Taljaard *et al.* 2003). Very little data are available on the salinity structure of the estuary, but Taljaard *et al*. (2003) surmise that the estuary is generally well stratified except when it is closed and that saline waters do not penetrate more than 7 km upstream even under low flow conditions. Under high flow conditions (i.e. >50 m^3/s) they predict that estuary is likely to be fresh throughout, with very limited saline intrusion at the mouth at times. Reduced levels of stratification have been reported during periods when the mouth is closed, except in the deeper parts of the estuary where salinity will remain close to that of sea water (~30 PSU).

Nutrient loading in the estuary (nitrogen, phosphorus and silicate) in the Present state is believed to be little different from that under Reference conditions. Taljaard *et al.* (2003) surmise that although nutrient inputs from agricultural activities along the river are likely to contribute to nutrient loading in the system, the lack of significant agricultural inputs in the lower reaches of the system allows for these nutrients to be taken up before they reach the estuary.

There is relatively little information on pollutant transport, other than sediment and nutrients, by the Orange-Senqu to the estuary. There are reportedly significant anthropogenic sources of pollution in the basin, particularly in the Vaal catchment which is heavily urbanised and contains much heavy industry including gold and coal mining (ORASECOM 2008). The Orange River and other smaller catchment are not as heavily developed but do receive discharges from waste water treatment works in the numerous small towns and urbanised areas along the river, many of which are not in compliance with the waste water discharge standards and licence conditions (ORASECOM 2008). Taljaard *et al*. (2003) presents data on trace metal concentrations in water at the Rosh Pinah, about 70 km upstream from the mouth of the estuary, for the period 1998 to 2003, and trace metal concentrations in the sediments in the estuary collected in 1997. These data are presented in Table 1**Error! Reference source not found.**. Concentrations of trace metals in the water entering the estuary are above guideline limits specified for the BCLME region (BCLME 2006), while those in the sediments are lower than the guideline limits. This suggests that most of the trace metal contaminants are not retained in the estuary, and are rather exported directly to the marine environment. Once these contaminants enter the marine environment they are likely to be rapidly diluted and are unlikely to pose a major risks to marine biota. Data on concentrations of other toxic substances in the water from the Orange-Senqu River, including Persistent Organic Pollutants (POPs), is even more limited than that for trace metals. Vosloo & Bouwman (2005) surveyed a number of sites in the Orange-Senqu catchment and found that concentrations were elevated well above guideline limits. Total concentrations of Toxic Equivalent Factors (TEQs), calculated as the sum of individual compounds, were high in some parts of the catchment (up to 22 ng/kg), but were low near the mouth (0.23 ng/kg), well below the action level determined for the USA.

Table 1. Trace metal concentrations in the Orange-Senqu River near the top of the estuary and in sediments in the estuary (from Taljaard *et al.* 2003).

	Water		Sediment		BCLME Guidelines	
	Mean	Range	Mean	Range	Water	Sediment
Fe	947	10-5200	-	-	-	-
Mn	40	10-200	-	-	-	-
Cu	33	10-80	10.8	7.8 – 17.2	1.3	18.7
Zn	32	10-80	23.1	14.7 – 51.9	15	124
Cd	<10	5.5-0.68	0.032	0.017 – 0.06	5.5	0.68
Pb	<20	4.4-30.2	5.4	2.4 – 8.7	4.4	30.2

2.2. Impacts on estuary biota

From a botanical perspective, the Orange-Senqu estuary is described as a delta-type river mouth comprising of a wide range of habitats including braided troughs interspersed with sand and mud banks, pans, channel bars and small islands, and a tidal basin and a saltmarsh on the southern bank (Taljaard *et al.* 2003). Estuarine wetland occupies approximately 1 842 ha around the Orange Senqu mouth (Bornman & Adams 2010). The common reed *Phragmites australis* along with the submerged macrophyte *Potamogeton pectinatus* dominate around the mouth, while species such as *Sporobolus virginicus* (brakgras) and *Scirpus maritimus* dominate on the islands further upstream. Peripheral marshes are dominated by *Sporobolus viginicus*, along with various herbs, sedges and grasses such as *Cotula coronopifolia*, *Juncus kraussii* (sharp rush), *Apium graveolens* and *Cyperus laevigatus. The* salt marsh areas comprise a mosaic of species including *Cotula coronopifolia*, *Triglochin* spp., *Juncellus laevigatus*, *Sporobolus virginicus* and *Sarcocornia pillansii, with the latter species* dominant in the salinized lower floodplain areas. Taljaard *et al*. (2003) estimated that approximately 90% of the salt marsh area on the southern bank of the estuary has been lost due to anthropogenic influences, and is now a barren saline desert. Loss of the salt marsh has been attributed to a variety of anthropogenic impacts including leakage of process water from the neighbouring diamond into the salt marsh, effects of windblown dried slimes dam sediment on the marsh vegetation, flood protection works, a road and a causeway constructed near the mouth of the estuary, and changes in mouth dynamics (Taljaard *et al*. 2003, Bornman *et al.* 2004, Shaw *et al.* 2008, Bornman & Adams 2010, van Niekerk *et al*. 2003). Under natural conditions water would have entered the saltmarsh from the main channel during the summer floods, while in winter, when the mouth closed this area would have been inundated due to back flooding.

No comprehensive surveys of phytoplankton have been conducted for the Orange-Senqu estuary. Taljaard *et al*. (2003) are of the opinion that prior to the development of large impoundments, high flows and flushing would have mostly likely have prevented the establishment of resident phytoplankton populations, while benthic microalgae biomass may have been high in backwater areas. Increased retention time in the estuary under Present day conditions, resulting from reduction and alteration of flows as well as nutrient enrichment, would most likely promote the growth of phytoplankton. The proliferation of phytoplankton would be at the expense of large plant species, as the phytoplankton reduces the amount of light reaching the larger rooted plant species, thereby inhibiting their growth. In addition, the decomposition of phytoplankton may lead to oxygen depletion or hypoxia, which in turn can kill fish and invertebrates, and can cause a general reduction in biodiversity.

The earliest surveys of the fauna of the Orange-Senqu Estuary, conducted between 1956 and 1958, indicate that the estuarine invertebrate fauna were extremely depauperate and that the Orange-Senqu River in fact lacked an estuarine component (Brown 1959). It was reasoned that this lack of an estuarine component was a due to the fact that the Orange-Senqu River possessed no true estuary, as river flows dominated and no appreciable variation in salinity, caused by the sea, existed within the lower reaches of the river (Brown 1959). This is considered by most authors to be representative of the Reference condition of the system (Taljaard *et al.* 2003, van Niekerk *et al.* 2008). The situation is substantially different in the Present state where van Niekerk *et al.* (2008) recorded 16 and 25 zooplankton and 4 and 7 benthic macrofauna taxa in summer and winter respectively (compared with only 3 zooplankton and 4 benthic macrofauna taxa recorded by Brown 1959). Similarly, the number of fish taxa and abundance of fish in the estuary seems to be dramatically higher in the Present state than under Reference conditions. Detailed surveys conducted by Harrison (1997), Seaman & Van As (1998), and van Niekerk *et al*. (2008) revealed the presence of at least 33 species of fish in the estuary, compared with only two species recorded by Brown (1959), albeit from what was most likely less sampling effort.

At least a third of the fish species (34%) recorded in recent surveys are estuary associated species (i.e. able to breed in estuaries or use them to some extent as a nursery area), one quarter (24%) are marine species that are probably feeding in the estuary, and the rest (42%) freshwater species (van Niekerk *et al*. 2008). Historically, the number of marine species utilising the estuary and their residence time is likely to have been much lower than in the Present state due to sustained freshwater flows during winter, while it is anticipated that freshwater species, which previously retreated to the upper reaches of the estuary in response to increased salinity, would now persist in the estuary throughout winter. The impacts that an altered flow regime (75% seasonal reversal) may have had on recruitment, migratory or spawning cues are currently unknown.

There are no historic (pre-1980s) data available on birds of the Orange-Senqu estuary, other than anecdotal notes provided by Brown (1959), who recorded the presence of Greater and Lesser flamingos, a number of duck species and waders (Avocet). Detailed bird count data are available from 1980 only, and present a rather disturbing picture of declining bird numbers. Numbers have declined from over 20 000 individuals in the 1980's to an average of around 6 000 individuals in the period 1995-2001 (Anderson *et al.* 2003). This decline has been attributed mostly to the collapse of populations of Cape Cormorants and Common Terns frequenting the estuary, thought to be due to a combination of factors including depleted food reserves, increased disturbance by humans, changes to the architecture of the mouth and islands with a consequent effect on roost site availability, disease and oiling (Anderson *et al*. 2003). Several other waterbird species, both freshwater and saline species, and several waders that were particularly numerous in the 1980s (Ryan & Cooper 1985) have not subsequently attained their original numbers. The reason for this is unclear, but it is thought to be related to the deterioration of the saltmarsh and the corresponding decrease in available mud-flat habitat for many of these species (Anderson *et al*. 2003).

3. IMPACTS ON THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM

Aside from the impacts that the Orange-Senqu River has on its estuary, there are a number of important impacts on the broader marine environment that need to be considered. These impacts are addressed in this section following a brief description of the marine environment in this region, otherwise known as the Benguela Current Ecosystem.

3.1. Impacts on physical oceanographic processes

The marine ecosystems off the south west coast of Africa are influenced by the Benguela Current System (BCS), which extends along the eastern edge of the southern Atlantic Ocean between Cape Agulhas (South Africa) and the Congo River mouth (Angola). The BCS is one of four major eastern-boundary current systems that are characterised by the wind-driven upwelling of cold, nutrient rich water (Shannon & O'Toole 1998). Benguela current originates from the South Atlantic Circulation, which circles just north of the Arctic Circumpolar Current. The system is bounded by two warm currents; the Agulhas Current in the south and the Angola Current in the north.

The naturally cool temperature of the Benguela current (average temperature 10-14^{o}C) is enhanced by the upwelling of cold nutrient-rich deep water (Shannon 1985). The upwelling system is driven by strong southerly and south-easterly winds which are deflected by the Coriolis forces (the rotational force of the earth that causes objects in the southern hemisphere to spin anticlockwise). These prevailing conditions deflect the surface waters offshore allowing cold, nutrient rich water to well-up along the coast. The upwelling intensity is dependent on the strength and continuity of these winds and has been found to vary interannually. In the southern section of the BCS the south-easterly trade winds are highly seasonal with their maximum in spring and summer. Upwelling intensity also varies geographically, according to the width of the continental shelf and intensity of southerly winds, such that upwelling is most intense where the wind is strongest and the shelf is narrowest (Sakko 1998). Water temperature, salinity and nutrient levels in the marine environment are strongly influenced by upwelling intensity, with minimum temperatures and maximum nutrient levels occurring in conjunction with upwelling events (Branch & Griffiths 1988).

The Range-Senqu River drains into the southern section of the BCS adjacent to the widest part of the continental shelf and at the southern boundary of the Lüderitz-Orange River Cone upwelling cell. This upwelling cell forms the boundary between the northern and southern Benguela systems and is characterised by strong winds, high turbulence, strong offshore transport and low phytoplankton levels (Hutchings *et al*. 2009). The discharge from the Orange-Senqu estuary typically forms a plume of buoyant, nutrient-rich freshwater where it drains into the sea, the nature of which, is shaped by the discharge volume and prevailing wind conditions (Shillington *et al*. 2006, Gan *et al*. 2009).

Buoyant discharge plumes have been known to modify alongshore and cross-shelf upwelling circulation in the upper water column, and can strongly influence near-shore circulation patterns (Gan *et al*. 2009). During upwelling favourable conditions, the surface-trapped plumes move offshore becoming thinner, thereby strengthening the seaward transport of the plume and the shoreward transport beneath. The actual upwelling intensity is unaffected, however, as there is little to no effect on the water column below 20 m (Gan *et al*. 2009, Chao & Boicourt 1986). During down-welling favourable conditions, the freshwater plume typically forms a downwind coastal jet which elongates, accelerates and deepens along the coast (Gan *et al*. 2009, Chao and Boicourt 1986). Alongshore currents are enhanced geostrophically along the inshore edge of the plume and weakened along the off-shore edge, due to pressure gradients created by differences in buoyancy between the plume and seawater (Gan *et al*. 2009).

Under normal circumstances, the flow from the Orange-Senqu River is so small that it plays no role in determining near-shore circulation. During severe floods, however, the river plume has exerted some control over coastal circulation patterns (Shillington *et al*. 2006). In the absence of strong winds the buoyant discharge plume from the 1988 Orange-Senqu River flood formed an eddy with a diameter of 42 km, and a 10-15km band of coastally-trapped shallow, warm, low-salinity water which travelled up to 200km southwards of the mouth (Shillington *et al*. 2006). When south-easterly wind intensified, however, the discharge plume moved north with a deflection to the left caused by the Coriolis Force (Shillington *et al*. 2006). In terms of run-off, this flood was the largest historic flood on record (24.3km^3) (Rogers and Rau 2006), but was by no means exceptional, and was estimated to be a 1 in 10 to 15 year event (Swart *et al*. 1990).

3.2. Impacts on marine sediments

The mass of sediment discharged by the Orange-Senqu River is estimated to be around 17 x 10^6 t/year (Bremner *et al*. 1990). While this may be small in comparison to the world's leader, the Ganges-Brahmaputra which discharges in the order of 1 670 x10^{6}t/year, it still represents a significant volume of sediment entering the Benguela Current System each year. Present day discharges of sediment from the Orange-Senqu system are considerably lower than those recorded prior to the 1960's but of a similar magnitude to those reported for geological time scales (Table 1). A concomitant change has also occurred in the texture of the suspended sediment load carried by the river, which has changed from silt-dominance in pre-1970 material, to clay dominance since this time (Bremner *et al*. 1990). Both of these effects have been attributed to agricultural malpractices in the parts of the catchment (NE Cape in South Africa) in this early period (Rooseboom & Mass 1974), and the fact that easily erodible topsoil was stripped from the Upper Orange catchment during the early 1930s, and the rapid increase in the number and size of dams that were constructed in the catchment in the early 1970s (Bremner *et al*. 1990). These changes are mirrored in the changes in the suspended sediment concentrations measured in flood waters in March 1988 (7.4 mg/l) compared with similar sized floods in April 1961 (17.4 mg/l), March 1965 (15.5 mg/l) and November 1955 (14.5 mg/l) (Bremner *et al*. 1990). Historically, the bulk of this sediment carried by was reportedly derived from the upper portion of the catchment from whence most of the runoff is also derived (Rooseboom & Mass 1974, Rooseboom 1974, 1975, 1978, Rooseboom & Harmse 1979), whereas this has now shifted to the lower catchment, below the major impoundments on the system. Bremner *et al*. (1990), list bank erosion and river bed scour, derived from the river channel downstream of the major dams situated near the Orange-Vaal confluence, as the main sources of sediment in the river in the 1988 floods. Large amounts of sediment were also removed from the estuary as well, with vertical scour of at least eight metres deep being recorded at the bridge (Swart *et al*. 1990), and lateral erosion of the salt marsh of about 400m (Bremner *et al.* 1990). The total volume of sediment discharged during the 1988 flood was estimated at 64.2 million tons, very similar to the mean annual sediment discharge of 60.4 million tons measured at Prieska/Upington (close to the mouth) between 1930 and 1969 (Bremner *et al*. 1990).

Table 2. Variation in sediment discharge rates of the Orange-Senqu River (after Bremner *et al*. 1990)

Period	Information source	Sediment discharge rate (x 10^6 t/y)
Geological time		
Late Cretaceous	Dingle & Hendey (1984)	24
Palaeogene	Dingle & Hendey (1984)	4.5
Neogene	Dingle & Hendey (1984)	0.8
Historical time		
?	Lisitizin (1972)	153
Pre-1921	Perry (1988)	119
1929-1934	Rooseboom & Mass (1974)	89
1934-1943	Rooseboom & Mass (1974)	56
1943-1952	Rooseboom & Mass (1974)	52
1952-1960	Rooseboom & Mass (1974)	46
1960-1969	Rooseboom & Mass (1974)	34
1980's	Bremner *et al*. (1990)[1]	<17

1. Cited as Rooseboom (pers. comm) by Bremner *et al*. (1990)

Once they arrive in the sea, sediments from the Orange-Senqu River are deposited in a submarine delta, and are dispersed north and south wards of the river mouth by wave action, longshore drift and subsurface currents. The submarine delta off the mouth of the river extends approximately 26 km seaward of the Orange-Senqu mouth and 112 km laterally (Rogers & Rau 2006). Littoral drift, driven by the south-westerly swells, moves most of the coarse material (sand and gravel) equatorward of the river mouth (i.e. into Namibia waters)(Rogers 1977), while the weak poleward undercurrent (De Decker 1970, Nelson 1989) carries silt and clay south of the mouth (i.e. into South African waters)(Rogers & Bremner 1991)

The section of the continental shelf opposite the Orange-Senqu River is termed the "Orange Shelf", and is the widest part of the Namaqualand shelf. It was formed by high sedimentation rates off the Orange-Senqu River in the Cretaceous period (Rogers & Rau 2006). It is up to 100 km wide and 200 m deep. Most of the terrigenous sediments off the west coast of southern Africa are in fact derived from the Orange-Senqu River, with smaller contributions coming from other rivers in the region (Olifants and Swartlynjies) (Rogers & Bremner 1991). Some of the material on the shelf is comprised of marine biogenic carbonates that are transported northward by longshore drift (De Decker 1988, Rogers & Rau 2006). Much of the fine silt and clay carried south by the inshore undercurrent, accumulates along a mudbelt south of the river mouth (Bremner *et al*. 1990; Compton and Wiltshire 2009). The mudbelt extends approximately 500 km southward from the Orange-Senqu River mouth to St Helena Bay and lies at a depth of 40 to 130 m (Rogers and Rau 2006). It is at its thickest (35 m) at the mouth of the Orange-Senqu River (De Decker 1986).. Mean particle size of the sediments in the mudbelt decreases southward due to the reduced influence of the river and the ability of the poleward undercurrent to transport only very fine materials (Rogers & Rau 2006). The marine biogenic component in the sediments, by contrast, increases southward of the mouth, indicating that there is a significant marine influence on the inner shelf, and that the Namaqualand mudbelt is not primarily derived from the southward transport of terrigenous sediment as was previously thought (Rogers & Rau 2006).

3.3. Impacts on marine water chemistry

Water in the main stem of the Orange-Senqu is reportedly generally of good quality with low levels of nutrients, except in localised areas, where the river runs through small towns where waste water treatment plants discharge poor quality sewage effluent into the river, for example along the Caledon, a major tributary of the Senqu, and in the Upington area in South Africa (ORASECOM 2008). Data on inorganic nitrogen and phosphate concentration near the mouth of the river and in the estuary presented by Taljaard *et al*. (2003) concur with these observations. They suggest that the amount of nitrogen and phosphate carried down by the river under the Present Day conditions (N mostly less than 500 µg/l and P mostly less than 60 µg/l) are little different from those in the Reference State (around 250 µg/l for N and 5 µg/l for P). These concentrations are similar to those reported for surface waters in the Benguela upwelling region where nutrient concentrations are naturally high (100-400 µg/l for N and 40-90 µg/l for P) (Chapman & Shannon 1985, Brown & Hutchings 1987, Brown 1992). As such, the river cannot be considered a major source of nutrient for the marine environment, nor is it likely the nutrient input from the Orange-Senqu River plays a significant role in the overall productivity of the marine ecosystem.

Transport of pollutants by the Orange-Senqu River to the sea is also low as described earlier. While concentrations of trace metals in the water entering the estuary are above guideline limits specified for the BCLME region (BCLME 2006), once these contaminants enter the marine environment they are likely to be rapidly diluted and are unlikely to pose a major risk to marine biota. Similarly, Vosloo & Bouwman (2005) report that concentrations of Toxic Equivalent Factors (TEQs) in the river are low near the mouth (0.23 ng/kg), well below the action level determined for the USA.

3.4. Impacts on marine biota

Marine ecosystems off the Orange-Senqu estuary are situated near the centre of the Namaqua bioregion, a cool-temperate bioregion that extends from Sylvia Hill, north of Lüderitz in Namibia, to Cape Columbine in South Africa (Lombard *et al*. 2004). This bioregion is characterised by strong wave action, intensive upwelling, nutrient rich water, high levels of primary production both on the shore (algae) and offshore (phytoplankton), high filter feeder and grazer biomass (zooplankton, molluscs, and fish), large populations of higher predators (marine mammals and birds), and a number of major commercial fisheries. The influence of the Orange-Senqu River on these communities is mostly like small and localised though, due to rapid dilution and distribution of material discharged from the river.

It has been already been highlighted, for example, that nutrients output from the river is unlikely to influence primary production in the offshore marine environment to any great extent. The influence of outputs from the river on phytoplankton communities appears to be restricted to a handful of diatom species that appear more abundance off the mouth of the Orange-Senqu and other river mouths in the region (e.g. Kuenene) (Holzwarth *et al*. 2007). These authors speculate that this may be due to reduced salinity in the surface waters and/or other river-specific influences (e.g. nutrient, trace metals and sediment inputs).

There are some clear impacts from the river on offshore benthic invertebrate fauna, though. Oxygen levels in the sediments of the Orange River Delta (> 2m/l O_2) are considered to be sufficient to support benthic fauna (Rogers & Rau 2006), but high sedimentation rates in this area, estimated at 3.70 mm/year (Meadows *et al*. 1997), seemingly inhibit the development of such communities. Levels of bioturbation in these sediments are very low, with laminations in the sediment providing a relatively undisturbed record of historical flood events (Mabote *et al*. 1997). Elsewhere on the shelf, where sedimentation rates are lower, infaunal burrowing activity is sufficient to destroy these laminations (Mabote *et al*. 1997, Meadows *et al*. 1997, Meadows *et al*. 2002, Rogers & Rau 2006). High sedimentation rates in the Orange River Delta also contribute to low organic matter content in this area (Rogers 1977, Mabote *et al*. 1997). Faecal pellets in sediments increase in the mudbelt south of the Orange River Delta (where they are rare) to off the Olifants River (200 km to the south) where over 90% of the sediment is composed of faecal pellets (Birch 1975, Rogers & Bremner 1991). A corresponding increase in abundance of polychaete worms has been noted along this trajectory (Christie 1975).

The Benguela Current System supports a number of major offshore commercial fisheries including demersal (bottom) trawl and longline fisheries that focus primarily on hake, midwater trawl fisheries that focus on horse mackerel, purse seine fisheries focussing on sardine and anchovy, pelagic longline fisheries focussing on tuna, swordfish and sharks (Crawford *et al*. 1987, Griffiths *et al.* 2004). Closer inshore there is also an important commercial fishery for rock lobster, and smaller operations targeting sole and linefish (snoek). The area off the Orange River mouth is not particularly important for any of these fisheries, except the west coast sole (*Austroglossis microlepis*), presumably owing to low biomass of the other target species in this area. The area off the Orange-Senqu mouth may, however, be important as a nursery and/or spawning ground for some species. Two stocks of *A. microlepis* exist in South African and Namibia waters, a southern population centred on the Orange-Senqu mouth and a northern population opposite the Skeleton coast (Crawford *et al*. 1987). As is the case with many other sole species (Le Clus *et al.* 1994), this one seems to favour areas of fine muddy sediment such as is found of the mouth of the Orange-Senqu River. Monkfish (*Lophius spp.*), one of the most valuable bycatch species in the bottom trawl fisheries in the Benguela System, also reportedly spawns off the Orange-Senqu River mouth (Hampton *et al.* 1999, Hampton 2003). Presumably, changes in sediment discharge from the river must have had some impact on these two species, although it is not clear whether this has been good or bad and whether it will be possible to isolate these effects in the face of many decades of intense exploitation.

The distribution of deep water hake, *Merluccius paradoxus*, the dominant species in the demersal trawl fishery in both South Africa and Namibia, spans the whole of Namibia and the South African west coast. The bulk (65-75%) of the stock is located in South African waters. Spawning seems to be confined to the area south of Cape Town (Strømme *et al.* 2004, 2005a, b). Eggs, larvae and juveniles are carried northwards up the west coast but remain south of the Orange-Senqu River until they reach at least 10 cm in length. Thereafter, the small fish begin to move off the shelf into deeper water, spreading north and south, with a considerable portion moving northwards across or along the edge of the Orange shelf up into Namibian waters. Sediment originating from the Orange River that is distributed on the shelf presumably influences the distribution or movement of fish in the nursery area south of the river to some extent. It is not clear how important this is though. Hydrographic features on the Orange shelf areas are reportedly highly dynamic, with varying origin of the water masses, and may temporarily form a barrier to the movement of fish on the shelf (Strømme *et al.* 2004). The role of the Orange River in this is also not clear, but probably minimal.

One of the major nursery grounds for pelagic fish in the Benguela (sardine and anchovy) is located on the continental shelf south of the Orange-Senqu River mouth (Hutchings *et al*. 2009). These species spawn on the southern part of the west coast and on the Agulhas Bank (south of the subcontinent). Eggs and larvae are transported in a strong shelf-edge jet up the west coast at which point the pre-recruits move inshore towards the nursery grounds. The influence of the Orange-Senqu River on these processes is probably minimal though. Significant stocks of adult sardine and anchovy are reported to occur within 30 nautical miles off the Orange-Senqu River mouth, but these are not exploited for logistic reasons (CSIR 1994, BCLME 2004).

Rock lobster occurs in commercially exploitable densities along a 900-km length of coastline either side of the Orange-Senqu River, from about 25°S in Namibia to Cape Town in the south (Crawford *et al*. 1987). The area immediately south of the river is not considered a good fishing ground for this species, and supports only a small portion of the South African stock. Less than 1.1% of the Total Allowable Catch (TAC) for South Africa has been allocated in this area in recent years (BCLME 2004). By contrast, the main commercial fishing area for rock lobster in Namibia is located just north of the Orange River (BCLME 2004). Rock lobster stocks in both countries are severely depressed at the moment, reportedly due to overfishing (Griffiths *et al*. 2004). This most likely has little nothing to do with the Orange-Senqu River.

Colonies of breeding seabirds in the vicinity of the Orange River mouth, located mostly in Namibia, are currently in decline. African Penguins, for example, have reportedly dropped from over 40,000 breeding pairs in 1956 to fewer than 1,000 pairs in 2003, while Cape Gannets have dropped from 0.47 birds/ha in 1956 to 0.02 birds/ha in 1996 (BCLME 2004). This was thought to be due to food scarcity, which resulted in poor recruitment to colonies, although some young birds have emigrated to other colonies to the north and south. The food shortage was reportedly caused by the collapse of Namibian sardine and anchovy stocks, and a decreased abundance of gobies in Namibia, caused by the Benguela Nino of 1994/95 (BCLME 2004). These changes most likely also contributed significantly to reduction in abundance of piscivorous bird populations on the Orange-Senqu estuary (cormorants and terns), and are not related to the condition of the river or estuary itself at all.

The influence of the Orange-Senqu River on nearshore marine biota is likely to be greater than for the offshore environment, especially in the surf zone which is often described as closed system (McLachlan 1981). Taljaard *et al*. (2003) are of the view that the export of nutrients, sediment and detritus to this area is undoubtedly important. They suggest that nutrients from the river serve to stimulate phytoplankton and zooplankton production in the nearshore marine environment, and ultimately, the larval, juvenile and adult fish that depend on this food source. Detritus may be broken down into useful nutrients, serve as a substrate for micro-flora and fauna or be consumed directly by detritivorous fish and invertebrates. Sediment export replenishes the nearshore habitats that are continuously eroded by oceanic currents and also provides a refuge for many fish by increasing turbidity. Turbidity, in turn, will serve to increase the catchability of many species, especially the larger individuals that move into the turbid environment in search of concentrated prey. The freshwater plume centred on the mouth of the estuary will provide cues for the migration of estuarine-dependent juvenile and adult fish into and out of the estuary. The strength of these cues will ultimately dictate how many individuals of these species recruit into the marine fisheries. Historical changes in the amount and seasonality of freshwater runoff to the estuary and ultimately to the sea would almost certainly have influenced the community composition and abundance of fish and invertebrate communities surrounding the mouth of the estuary. The seasonality of freshwater flows reaching the estuary, and hence the sea, have effectively been reversed (winter flows are often higher now than those in the historical high flow summer period) (Taljaard *et al.* 2003), and presumably must be having some impact on those species that rely on seasonal cues for entering or exiting the estuary.

The influence of episodic events such as the 1988 floods extend further from the mouth, and in the latter instance led to mass mortalities of intertidal organisms up to 140 km south of the mouth (Branch *et al*. 1990). Limpets, mussels, octopus, chitons, urchins, red bait, barnacles, reef worms and almost all rock lobster and kelp were eliminated from the rocky shores within a 10 km radius of the mouth as a direct result of the flood. The causes of mass mortalities were reasoned to be due to lowered salinity, increased turbidity which reduced light penetration, and deposition of silt and organic matter which resulted in depletion of oxygen level in the water column (Branch *et al*. 1990). Following the floods, previously denuded rocky shores became dominated by opportunistic foliar algae (Branch *et al*. 1990).

4. PRIORITIZED IMPACTS AND LIKELY CAUSES

Of the twenty-three common GEF transboundary issues recognised internationally, those emerging as priority issues in this study include modification of stream flow and modification of ecosystems. Impacts of the issues on the Benguela Current marine environment, mediated through anthropogenic impacts on the Orange-Senqu River, seem to be mostly confined to the estuary, and inshore marine environment in the immediate vicinity of the estuary, although deposition of sediment on the continental shelf may have more wide reaching effects.

Historically the Orange-Senqu estuary was a temporarily open/closed estuary, closing briefly in the winter low flow periods and/or as a result of wave action building up the sand bar at the mouth. Under present day conditions, however, hydro power releases during the winter months and massive abstraction of water from the catchment in summer have modified the natural flow regime of the river to such an extent that the estuary mouth seldom, if ever, closes. This in turn, prevents water from building up in the system and flooding the adjacent salt marsh areas. Moreover, mouth closure, when it does occur, is now more likely to occur in summer than winter. Floods that would historically have reset the system in summer and inundated the saltmarshes and floodplain, have also been greatly reduced. Localised anthropogenic impacts such as the construction of roads, dykes, slimes dams near the mouth, have further degraded the estuary and associated ecosystems.

Changes in the volumes and seasonality of freshwater reaching the nearshore marine environment surrounding the estuary, along inputs of nutrients, sediment and detritus, have most likely influenced both abiotic (e.g. sediment transport, erosion and nutrient cycling) and biotic processes (e.g. recruitment) in this area. Further offshore, impacts are changes in river dynamics are probably restricted to deposition of sediment of the shelf which in turn may have affected abundance, distribution and recruitment success of some commercially important fish species and their prey to a limited extent.

Modification of estuarine and marine ecosystems in the Benguela Current System and modification of stream flow in the Orange-Senqu system are clearly closely linked, the latter being the primary cause of the former. The Preliminary Transboundary Diagnostic Assessment for the Orange-Senqu River Basin (ORASECOM 2008) highlights the fact that surface water resources of the Orange-Senqu Basin are highly utilized to the extent that the residual flows to the mouth represent only 25% of the natural MAR. South Africa is by far the largest user of water in the catchment, accounting for 95% of all water demand. The bulk of this (approximately 60%) is utilised by the irrigation sector where considerable scope for savings exist. ORASECOM (2008) list the primary causes of the high level of water use in the agricultural sector as:

- the predominance of flood irrigation and the application of excess water, which also risks salinity problems and low quality return flow water;
- the cultivation of crops that require large applications of water but which yield a low unit area economic return;
- High evaporative losses from spray and centre pivot systems, particularly for broad leaved plants such as maize;
- Significant transmission losses in distribution systems;
- The lack of any effective demand management and the consequent virtually unrestrained use of water by farmers; and
- Unlicensed abstractions.

Taljaard *et al*. (2003) recently undertook an assessment of the water requirements of the Orange-Senqu estuary using methods prescribed by the South African Department of Water Affairs and Forestry (DWAF 1999), for the determination of freshwater requirements of estuaries in this country. The study highlighted the ecological importance of this system including the fact that it is recognised as an internationally important wetland for migratory birds (RAMSAR site), that it is ranked as the 7th most important system in South African in terms of conservation importance, that it represents a unique ecosystem on what is otherwise a wave exposed, hyper-arid coast with few freshwater inputs and that it is the only large estuarine nursery area in the region, supporting significant populations of estuarine and marine invertebrate and fish species. In accordance with these characteristics, and guideline adopted by the South African Government (DWAF 1999), Taljaard *et al*. (2003) point out that the recommended ecological category (REC) for the system, defined by the level of protection that should be assigned to the system, should be a minimum Category A (i.e. unmodified or natural) or the best attainable state, given existing anthropogenic impacts to the system other than flow modification. These authors considered that anthropogenic developments along the banks of the estuary (i.e. non-flow related modifications), such as the road across the salt marsh area, seepage of saline water from mining developments and human disturbance (of birds) system, preclude the attainment of a Category A status through flow restoration alone, and thus recommended that the best attainable state for the system was a C-category (i.e. moderately modified), but included a strong recommendation that mitigating actions to reverse modifications caused by the non-flow related activities and developments in the estuary be investigated by the responsible authorities. Estimated change is flow required to restore the Orange-Senqu estuary from its current state of a Category D (largely modified) to a Category C, required that flow during spring and summer (Sep-Feb) be increased by up to 154% (average for all months = 106%) and that flows during autumn and winter be reduced by up to 69% (average for all months = -9%).

Recommendations from this study were never adopted by the South African Government possibly owing to the low level of confidence assigned to the study by the authors (Confidence = Low), owing primarily to the fact that the study was conducted a desktop level only (i.e. no new data were collected for the study).

5. ISSUES TO ADDRESSED

A number of important issues affecting the Orange-Senqu estuary and adjacent inshore marine environment arising from anthropogenic induced changes to the Orange-Senqu River and particularly volumes and seasonality of freshwater flows reaching the estuary, have been identified in this study. Amongst the most significant of these are changes in bird fauna on the estuary, sediment flux to the marine environment, and possible impacts on nearshore marine fisheries. Little information is available on current use or dependence on available resources in the estuary and adjacent marine environment, and the likely socio-economic impacts of historic changes in the ecological functioning and health of this environment. A preliminary study was undertakento assess the ecological freshwater requirements for the Orange-Senqu estuary, (Taljaard *et al*. 2003), but this study was limited in as much as it was conducted at a desk-top level only, it did not include any socio-economic considerations, and did not consider impacts of altered flows on the marine environment. Detailed recommendations were included in this study on information required to enhance understanding on the current state and functioning of the system and hence confidence in the assessment of flow required to restore ecological functioning and associated environmental good and services provided by the system. Some of these requirements have been addressed through subsequent studies (e.g. BCLME 2008, Bornman 2009) but many still need to be addressed (e.g. flow gauging, water quality and microalgae assessments). There also remains a dearth of information on the socio-economic value of environmental goods and services produced by the estuary and adjacent inshore marine environment. Detailed information on these aspects would be invaluable for improving confidence in estimates of the minimum freshwater requirements to sustain ecological functioning and the delivery of these goods and services, and in motivating for the appropriate quantities of water to be made available for the estuary. It is recommended that any future assessment of the freshwater requirements of the system follow procedures developed as part of the South African National Water Resources Classification System (Dollar *et al.* 2006, Brown *et al*. 2006) and/or methods developed for the determination of the ecological freshwater requirements of estuaries in South Africa (DWAF 2008). These approaches both include requirements for assessing the value of goods and services produced by the entire catchment and in the case of the former method, trade-offs that exist with respect to allocation of water within the system. Such a study should also take account of any projected future changes in climate (temperature, rainfall and evapo-transpiration rates) for the region under an altered global climate regime.

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