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River connectivity and fish migration considerations in the management of multiple stressors in South Africa

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Abstract. People throughout the world depend on the services we derive from freshwater ecosystems. Human land-use activities often affect the quality, quantity and habitat of freshwater ecosystem, which need to be carefully managed to ensure their integrity and provision of services is sustainable. In South Africa, legislation has established resource-directed measures to attain a sustainable balance between the use and protection of water resources. These procedures have been implemented in most of South Africa's nine water-management areas, resulting in new legislation to protect these resources. Unfortunately, very little protection has been afforded to river connectivity maintenance and fish migrations. For water storage and flow regulation for agriculture and other resource use activities, >610 formal dams and ~1430 gauging weirs have been constructed that act a partial or complete barriers to fish migration on river ecosystems. Only ~60 fish passage structures have been built, but many are not functional. River connectivity and fish migration management appears to be a shortcoming of the existing management approach for multiple stressors.

Additional keywords: fish passage, resource protection, resource use, sustainability, water resources management.

Received 18 May 2019, accepted 1 July 2019, published online 16 July 2019

Introduction

Freshwater ecosystems provide a range of valuable, and often irreplaceable, ecosystem services, but are also among the most endangered ecosystems globally (Dudgeon *et al.* 2006; Rodell *et al.* 2018; Du Plessis 2019). In South Africa, water scarcity is exacerbated by the high demand for resources by diverse resource-use sectors (e.g. agriculture, urban communities, mining and industry) that affect the well-being of our aquatic ecosystems (Rivers-Moore *et al.* 2011; Du Plessis 2019). The synergistic effects of land-use change and associated water quality, changes in flows and habitat and disturbance to wildlife stressors are recognised threats to the well-being of river ecosystem in South Africa. These multiple stressors are sometimes considered to be poorly managed (Hsu *et al.* 2013; van Rooyen *et al.* 2017). South Africa has nationally committed to achieve a sustainable balance between the use and protection of water resources and internationally commits to achieving the Sustainable Development Goals (SDGs; Dickens *et al.* 2019). To achieve this, South Africa has established policies and legislation for the management of the use and protection of water resource to achieve sustainability (King and Pienaar 2011).

The well-being of water resources and the provision of ecosystem services that people depend on are intrinsically linked to the well-being of both the terrestrial and aquatic

[1]All authors contributed to the preparation and writing of this paper.

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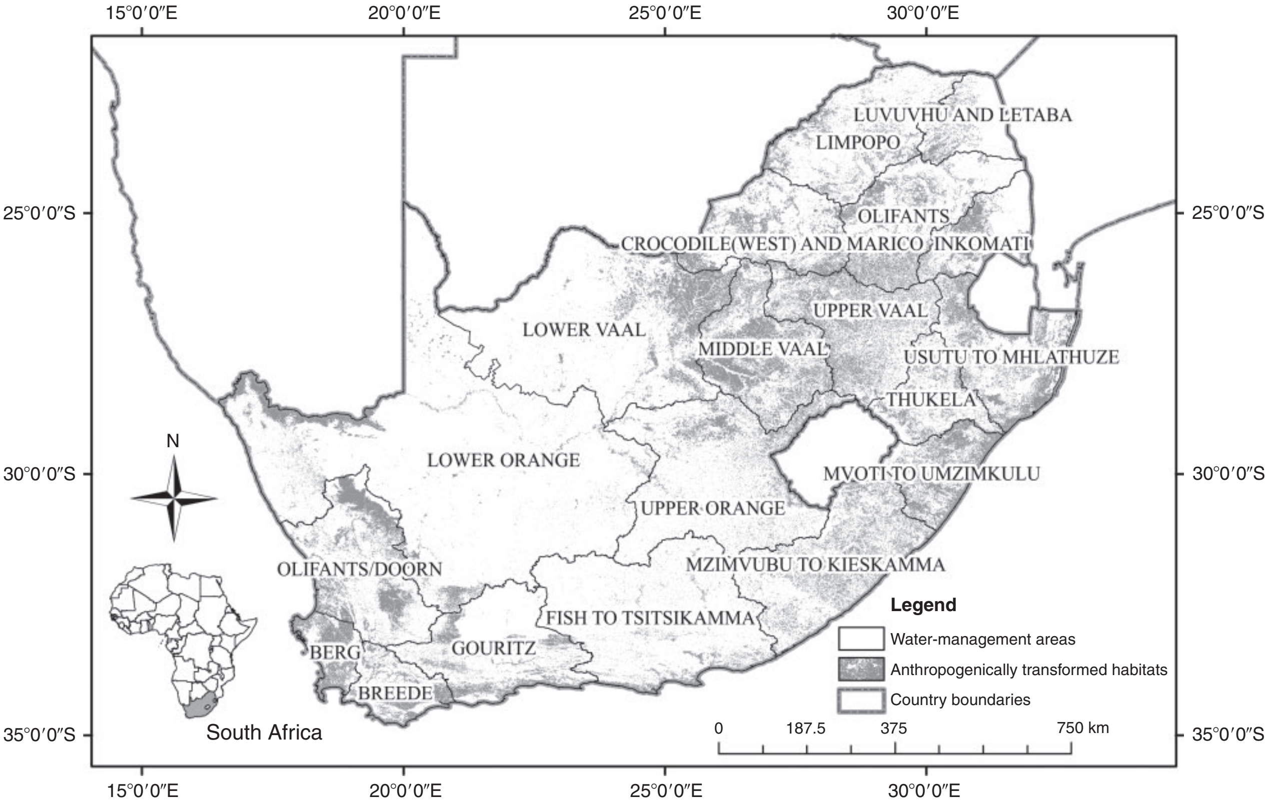

Fig. 1. The 19 water-management areas in South Africa used for the implementation of resource-directed measure as required by the *National Water Act* (Act 108 of 1998, South Africa), with anthropogenically transformed habitats associated with land-use changes (data obtained from Department of Environmental Affairs 2016).

ecosystems and connections between these systems (Dugan *et al.* 2010). Water flows between surface and subsurface ecosystems, from terrestrial ecosystems into wetlands, rivers, lakes and flood plains, with the succession of rivers representing a connected but changing system. In addition, relationships between resource users, stressors and receptors in ecosystems, and the upstream, lateral and downstream movement of biota within aquatic ecosystems, represent important water-resource connectivity (Stanford and Ward 1992; Silva *et al.* 2018). Migratory fishes represent system connectivity and depend on multiple habitats and connectivity between habitats along river ecosystems. These fish are socially and ecologically important and vulnerable to multiple stressors and resource degradation (Ziv *et al.* 2012; Dugan *et al.* 2010; O'Brien *et al.* 2018*a*).

The increasing growth of South Africa's population and the development of natural resources is driving changes to the quality and availability of ecosystem services and the well-being of natural resources themselves (Giannecchini *et al.* 2007; Jewitt *et al.* 2015; Cumming *et al.* 2017). Land-use changes for agriculture, peri-urban and urban development, infrastructure, mining and dam development in South Africa are negatively affecting terrestrial and aquatic ecosystems on large regional scales across the country (Jewitt *et al.* 2015). These impacts are considerable, relative to other countries, whereby, for example, South Africa has recently been listed as one of the world's worst performing nations (bottom 4%) in a Global Environmental Performance Index assessment (Hsu *et al.* 2013). Although the extent of land-use change across South Africa in 2014 is variable (Fig. 1), there has been a considerable increase in habitat transformation from 1994 after democracy (Shackleton *et al.* 2001; Jewitt *et al.* 2015). By 2014, anthropogenic land cover transformation of many provinces of South Africa exceeded 50% (Shackleton *et al.* 2001; Jewitt *et al.* 2015). This has resulted in the majority (>57%) of all river types in South Africa now occurring in a threatened or unsustainable ecological state (Driver *et al.* 2012; Lemley *et al.* 2015). Many (>46%) of the main-stem rivers in South Africa are currently classified as being severely modified or critically endangered (Driver *et al.* 2012).

Unfortunately, in South Africa water-resource management policy and legislation, often considered to be among the best in the world, is not being adequately implemented (Schreiner 2013) and, although progressive, important ecosystem components and associated processes, such as river connectivity and fish migrations, are not being adequately addressed. This paper reviews the importance of river connectivity and fish migrations in South Africa, and the multiple stressors associated with land use activities that threaten these processes that need to be formally integrated into water-resource protection policy.

Water-resource use in South Africa

In South Africa, 19 water-management areas (WMAs) have been established for the regional management of water resources (Fig. 1; King and Pienaar 2011; South Africa Department of Water Affairs 2013). All these WMAs have sustainable water resource

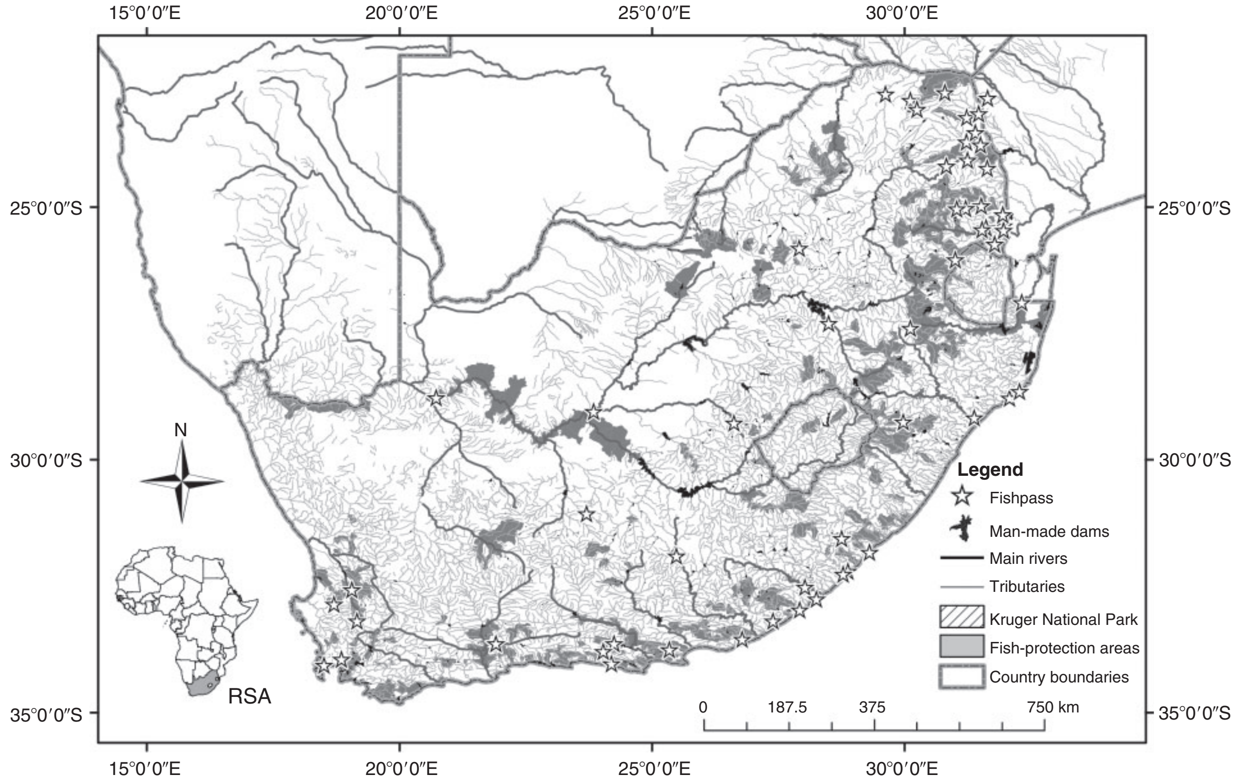

Fig. 2. Rivers and man-made lakes (dams) in South Africa with fish-protection areas as a part of the Freshwater Ecosystem Priority Areas of South Africa (Nel *et al.* 2011) and fish passage structures.

management challenges (King and Pienaar 2011). Water resources of the Upper, Middle and Lower Vaal, Olifants, Crocodile West, Limpopo, Luvuvhu and Letaba, Mvoti to Umzimkulu, Berg and Olifants–Doorn WMAs are all heavily used and, as a result, highly threatened (Driver *et al.* 2012; King and Pienaar 2011).

The irrigation sector for agriculture is the largest formal user of water (>60%) compared with domestic use (~27%) and all other formal users (~13%) that have transformed habitats (Fig. 1; Askham and Van der Poll 2017). These sectors compete with environmental flows and flows allocated to maintain basic human water needs (King and Pienaar 2011). For example, in the Olifants River WMA, although highly developed, between 2000 and 2013 alone 31.6% of the natural rangeland had been transformed primarily by agriculture development (20.1% increase; Gyamfi *et al.* 2016). These land-use changes have resulted in an increase of 46.97% in surface run-off generation coupled with increased soil erosion (Fig. 1; Gyamfi *et al.* 2016). In the Inkomati WMA, expanding agriculture, forestry and urbanisation over the past two decades has been identified as the dominant driver of water scarcity in the region. Jackson *et al.* (2016) describe the high variability of streamflow, increases in water resource use and competing water demands in the Inkomati WMA, which has resulted in water stress. Elosegi *et al.* (2010) identified land-use transformations in the Inkomati WMA that have disrupted natural flow-related drivers of ecosystem well-being, including increases in urbanisation, clearing of natural rangeland for agriculture and increased development of mines and industrial activity. In the Vaal River, water quality pollution events driven by surface run-off and effluent and sewage releases from urban areas, agriculture, mines and industries have severely affected the well-being of the system, which is now considered to be one of the world's most hard working rivers (Wepener *et al.* 2011; Du Plessis 2017; Naidoo 2017; Ramesh *et al.* 2018). Excessive land-use changes in KwaZulu–Natal that now exceed 50% and have affected flows and water quality in all the major rivers of the Usuthu to Mhlathuze, Thukela and Mvoti to Umzimkulu WMAs (Jewitt *et al.* 2015). In the uMngeni catchment, Namugize *et al.* (2018) found that land-use changes in the upper reaches of uMngeni catchment between 1994 and 2011 reduced natural vegetation by 17%, with an increase of cultivated lands and urbanisation.

An assessment by Rivers-Moore *et al.* (2016) showed that upstream to downstream extent of the uMngeni River has been severely affected by land-use activities and instream impoundments. The uMngeni catchment was found to be the most disconnected river in the province because of its closely located instream barriers and long-distance recovery potential of flow. According to South Africa Department of Water Affairs and Forestry (2004) increases in demand for irrigation water in the Inkomati catchment have driven the establishment of four major dams that store water to be released downstream for formal users and ecosystem protection (Jackson *et al.* 2016). In the Middle Olifants WMA, water requirement for irrigation is estimated to be 48% of the water requirements of the Olifants WMA (Biggs and Rogers 2003; Dabrowski and De Klerk 2013). The growing demands for domestic, mining, agricultural and industrial water in the upper and middle reaches have progressively reduced flows in the lower reaches of the Olifants River within the

Kruger National Park and surface flows have ceased for short periods during dry periods (Biggs and Rogers 2003).

Hall *et al.* (2011) state that damming of waterways alters the aquatic environment and surrounding landscape through sedimentation, channelisation, flooding and temperature changes. The passage of migratory species between feeding and spawning sites is interrupted, as is the exchange of nutrients. Caudill *et al.* (2013) stated that dams may affect fish behaviour and physiology in the migration corridor by altering water temperature, dissolved gas concentrations and other physiochemical conditions upstream and downstream of the dam.

Fish migrations in South Africa

The diversity of fish fauna in South Africa is varied and generally grouped into two assemblages including tropical 'Zambezian' and temperate fauna (Skelton 2001; Stankiewicz and de Wit 2006). This fish fauna diversity in the region aligns to three main ecoregions: (1) the East Coast region, which includes all the east-flowing rivers from the Limpopo River to the Umzimkulu River; (2) the Cape Floristic Region, from the Fish River to the Olifants–Doorn River; and (3) the Southern Temperate region, which includes the Orange River system and the southern coastal systems (Darwall *et al.* 2009). Although migratory fish are largely understudied in South Africa, it is estimated that >100 species have requirements for migration to different degrees (Whitfield 1990; Bok *et al.* 2007; O'Brien *et al.* 2018*b*). The migratory behaviour of local fishes includes potamodromy and diadromy in South African inland waters (Darwall *et al.* 2009). In South Africa, water resource areas that are representative of the diversity of fishes in South Africa, that maintain or have the potential to maintain a high diversity of species that are presently in a good ecological condition to provide refuge for a high diversity of fish have been established as fish-protection areas (Fig. 2; Nel *et al.* 2011). These priority areas include consideration for species that have migratory requirements.

Migratory fish occupy a range of ecological niches and perform many functions that contribute to the maintenance of the integrity of our river ecosystems and the services they provide (Fausch *et al.* 2002; Dugan *et al.* 2010). For example, in the rivers of the Mzimvubu to Kieskama WMA in South Africa, catadromous freshwater eels (*Anguilla* spp.) are the only large, indigenous, piscivorous fish, making them trophically unique. Numerous other diadromous fishes that occur in South Africa include the endemic freshwater mullet *Pseudomyxus capensis*, the speckled goby *Redigobius bikolanus* and the freshwater goby *Awaous aeneofuscus* (Whitfield 1990; Skelton 2001; Bok *et al.* 2007). By using different ecosystems through the different stages of their lifecycle, these diadromous species connect freshwater and marine environments and contribute to the circulation of nutrients and energy in ecosystems (McIntyre *et al.* 2016).

Globally, fish are good indicator species for aquatic ecosystems because of their sensitivity to water quality and because they accumulate toxins (Holmlund and Hammer 1999). Populations of migratory fishes that are exposed to a wide variety of habitats are indicative of the water quality of a variety of ecosystems. These species also have more specific requirements for various habitat types and for connectivity, making them excellent indicator species (Harris 1995). This function also includes a valuable role in terms of fish and river conservation because these species can be considered as umbrella species. Potadromous species such as the yellowfishes *Labeobarbus* spp. and the minnows *Enteromius* spp. can provide information regarding river health at a local scale, whereas long-distance catadromous species such as *Anguilla* spp. offer a unique insight into the physical, chemical and hydrological connectivity at a catchment scale.

Historically, many subsistence fishermen have relied on the seasonal migrations of fishes, such as the *Clarias gariepinus* spawning runs in Lake Sibaya (Bruton 1978), cichlid and cyprinid migrations in the Phongolo flood plain (Coetzee *et al.* 2015) and cyprinid migrations by San hunter–gatherers in the Senqu River (Plug *et al.* 2010). Recreational angling industries also target migratory fishes in the region, including yellowfishes *Labeobarbus* spp., with an estimated annual economic value of ~US$9.5 million annually in 2008 (Brand *et al.* 2009). Some of the South African migratory fish also have an effect on the local culture and spirituality, as is the case with the freshwater eels *Anguilla* spp., which are believed to have inspired the mythical creature 'Inkanyamba' that is part of the Zulu and Xhosa cultures of South Africa (Impey 2016). These ecosystems functions provided by migratory fish are increasingly threatened by increasing stressors associated with resource development and land-use changes, including development of dams and weirs for hydropower and irrigation, habitat loss for agriculture development, mining and industry, and the transfer of waste disposal (Baras *et al.* 2002). Because of their lifecycle vulnerabilities, migratory fish are almost twice as likely to become endangered than their non-migratory counterparts (Riede 2004), and are particularly vulnerable to the impairment of river connectivity. Impacts can lead to the delay or failure of migration, thus threatening the reproduction and survival of a given species itself (Baras *et al.* 2002). Dam development and the formation of barriers in South Africa have disrupted large-scale migration of fishes, including the anguillid eels and cyprinids (*Labeo* spp. and *Labeobarbus* spp.; Paxton 2004; Impson *et al.* 2008). Indirectly, changes in habitat and flow can threaten indigenous migratory and non-migratory species by easing the settlement of alien invasive species (Rahel and McLaughlin 2018). Maintaining river connectivity and the associated ecosystem service is even more of a challenge in regions that are prone to drought (Arthington and Balcombe 2011). Fish migrations in South Africa are not clearly linked to ecosystem sustainability and, as such, have not specifically been addressed in water resource management in South Africa. However, these important species and the processes associated with their migrations are intrinsically linked to ecosystem sustainability, and the lack of management of these processes may be why sustainability in the region is not maintained.

In South Africa many fishes with obligatory diadromous and anadromous migratory behaviour between marine, estuarine and freshwater ecosystems constitute an important part of South Africa's fish diversity (Whitfield 1990; Wasserman *et al.* 2011). These species have been directly affected by water quality and habitat stressors, as well as reduced river flows affecting connectivity between the rivers and the sea (O'Brien *et al.* 2009; Wasserman *et al.* 2011). Alien invasive fishes have also been identified as important stressors to the well-being of these species (Weyl and Lewis 2006). Numerous catadromous species, primarily represented by the anguillid eels, and potentially

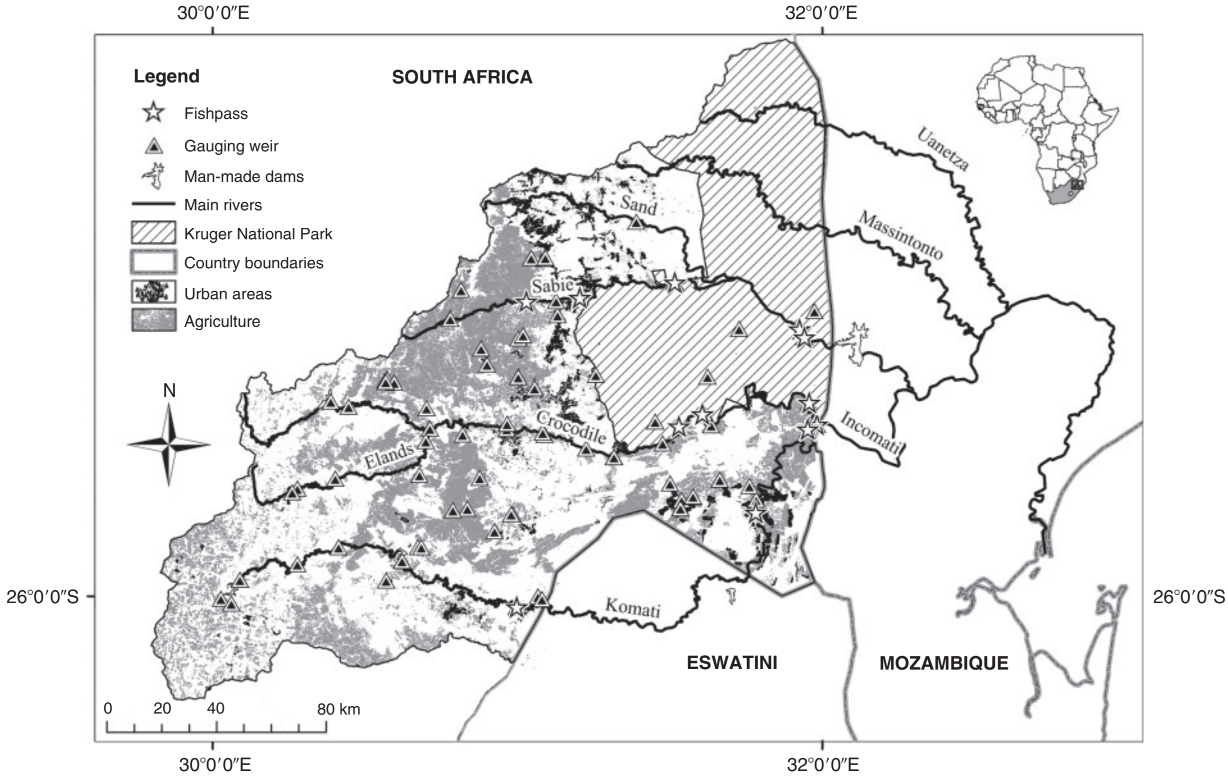

Fig. 3. Main rivers, man-made lakes (dams) and gauging weirs in the Inkomati Water Management Area of South Africa, with agriculture and urban areas and fish pass facilities included (data obtained from Department of Environmental Affairs 2016).

anadromous migrations of some *Hilsa* spp. for example, require access between marine and freshwater ecosystems (Skelton 2001; Bok *et al.* 2007). Most fishes in South Africa exhibit obligatory and facultative potamodromous and lateral migrations along rivers, predominantly from the lower to the upper reaches of rivers during spring, as well as between rivers and flood plains during high-flow periods (Cambray 1991; Merron *et al.* 1993; Skelton 2001; Plug *et al.* 2010). Unfortunately, very little is known about the migratory ecology of most fishes in the region, the requirements for migrations and the relationship between land-use activities, river connectivity, fish migrations and the well-being of ecosystems.

Fish passage in South Africa

Interest in maintaining ecosystem connectivity for fish migrations is limited in South Africa, as indicated by the limited information on fish passage science, design information and the construction of facilities in South Africa (Bok *et al.* 2007; Wasserman *et al.* 2011; Ziv *et al.* 2012; Silva *et al.* 2018). In South Africa ~60 fish passage facilities exist, of which only ~20% are known to be functional, 33% are ineffective and the functionality of the rest has not been evaluated (Bok *et al.* 2007). This can be compared to >610 formal dams that act as migration barriers in South Africa and ~1430 gauging weirs that act as anthropogenic barriers or partial barriers to migrations (Department of Water and Sanitation, Resource Quality Objective, Spatial Data, see http://www.dwa.gov.za/iwqs/report.aspx, accessed 15 May 2019; Fig. 3).

In South Africa some smaller abstraction weirs have been fitted with some sort of fish pass facility with varying levels of success, but no such facilities have been considered, or implemented, at larger impoundments (Bok *et al.* 2007). The lack of provision being made to facilitate fish migratory freedom has resulted in these water storage schemes being a large contributor to habitat fragmentation throughout the country and having a profound effect on fish distribution and conservation in general (Dugan *et al.* 2010; Nel *et al.* 2011). Although the effect of barriers on ecosystems is generally well known (Bourne *et al.* 2011), little has been done at the national level to mitigate these effects in South Africa. With the national reform of the water policy in South Africa, and the adoption of the *National Water Act* (Act 36 of 1998), resource sustainability and associated protection requirements have been proposed for resources. More recently the regulator of water resource use, the South African Department of Water and Sanitation, has initiated procedures to include fish passage in dam and weir construction. Fish passage is reasonably new in South Africa, and these infrastructure design processes are still dominated by the engineering sector (Bok *et al.* 2007; Silva *et al.* 2018), with limited input from experienced aquatic scientists for these structures to meet the migratory requirements of local fish species (Dugan *et al.* 2010). More recently, ichthyologists and water resource managers are starting to integrate hydraulic flow dynamics into formal infrastructure development processes of enhancing river habitat continuity, and engineers are beginning to gain a better understanding of the biological requirements when designing instream structures and hydraulic models (Bok *et al.* 2007; Silva *et al.* 2018). This new-found collaborative work is contributing to understanding limitations imposed on the designs by the respective disciplines, allowing for a more rapid implementation of effective fishways (Roscoe and Hinch 2010). Implementation of fishways into newly developed barriers is proving to be successful in mitigating for river habitat fragmentation, while research and development remains dynamic and ongoing (Silva *et al.* 2018). The provision of a bypass channel–rock ramp fishway combination tends to be the preferred alternative if topography and site conditions allow for it (Bok *et al.* 2007; Williams *et al.* 2012). Formal fishways tend to be designed around the vertical slot type, although, having to cater for lower flows as well, the pool and slot-type fishway is gaining popularity for catering to a wider variety of flows. What is clear is that each fishway has to be dealt with individually in order to successfully cater for the targeted species, and to be able to function within the boundaries of the hydrographs of the natural river or the artificial hydrographs induced by the infrastructure of a particular development. Fish passage science in South Africa is currently undervalued and should be elevated to contribute to the national sustainability vision for water resources and be aligned with international fish passage science, engineering and practice (Silva *et al.* 2018).

Water-resource protection measures

Water resource legislation was reformed in South Africa in 1998 (*National Water Act* (Act 108 of 1998), hereafter 'NWA') when the concepts of equity and sustainability were first formally introduced into water resource management. The NWA now recognises water as a scarce and precious resource that belongs to all the people of South Africa. The NWA also identifies all aspects of water on Earth as connected and that it must be managed as such. It is interesting that although the NWA recognises the concepts of connectivity, maintaining river connectivity and associated fish migrations, as well as stressors that affect migratory species, have not been adequately addressed.

The NWA protects the rights of all people to have water for their basic needs and the needs of aquatic ecosystems to remain sustainable, synonymous with environmental flows (King and Pienaar 2011; Arthington *et al.* 2018). Thus, the NWA directs the protection, use, development of, conservation, management and control of water resources, promoting the integrated management of water resources with the participation of all stakeholders (King and Pienaar 2011). Complementary to the NWA in South Africa, the National Water Resource Strategy is an instrument of policy that adopts an integrated water resources management (IWRM) process for the coordinated development and management of water, land and related resources (South Africa Department of Water Affairs 2013). This is to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (King and Pienaar 2011). South African IWRM aims to achieve a balance between the use of resources for livelihoods and the conservation of the resource to sustain its functions for future generations. Within the IWRM, there are two complementary strategies to achieve this balance: (1) resource-directed measures (RDM) to protect water resources by setting targets, goals and objectives for the desired condition of water resources in aquatic ecosystems; and (2) source-directed controls that specify criteria for controlling water resource use activities and their effects on aquatic ecosystems (King and Pienaar 2011; Dickens *et al.* 2019). Within the RDM procedures for South Africa, a vision for the resource is established that can be divided into three management classes for resources: Class I, high protection focus; Class II, moderate use and associated protection; and Class III, high but sustainable use. To achieve these classes and the vision to use and protect resources, the RDM includes a process of determining resource quality objectives (RQOs), or targets, and benchmarks for water quality, quantity, habitat and biota indicators that can be achieved to meet the desired class for a resource (King and Pienaar 2011; Dickens *et al.* 2019). The existing inclusion of biotic indicators in the RDM is limited primarily to the use of attributes of biological communities in indices of biological integrity, and does not adequately address important river connectivity and migration disruption considerations (Birnie-Gauvin *et al.* 2017; Silva *et al.* 2018). The RQOs are established for priority areas on a reach or regional scale where management is required because of existing high demands for the use of the resource that is ecologically important or vulnerable to use. RQOs are established for these areas where an important balance between the use and protection of resources is required. Indicators are then selected to ensure that both the protection and the use aspects of the resource are included in the RQOs. Based on the present-day status of each of these indicators, a trajectory of change required to achieve the management classes is established for implementation, especially in areas where the use of resources is excessive and or unsustainable. These RQOs are then recommended to the Minister of Water and Sanitation, who, after approval, writes them into legislation. These objectives are aspirational but realistically attainable and can inform achievement of SDGs.

At present, the RDM procedures have been implemented for most of the WMAs in South Africa, which has resulted in the establishment of new legislated objectives for managers to implement for the sustainable use and protection of resources (Dickens *et al.* 2019). Unfortunately, no RQOs have been established to mitigate the existing effects of multiple stressors, including the effects of barriers on the migrations of fish and associated river connectivity. From the 1970s, scientists have identified fish migrations as an important component of the well-being of communities in regions of high fish diversity and endemism in South Africa (Pienaar 1978; O'Brien *et al.* 2018*a*, 2018*b*) that need to be managed to maintain the well-being of the resource. Although important, the existing RDM procedures have not been applied to address river connectivity and fish migration processes.

Inkomati River basin example

The greater Inkomati River basin (and, in South Africa, a WMA) has been identified as one of South Africa's most ecologically important water resources, due, in part, to the high diversity of endemic fishes, with a large proportion of the WMA identified as a fish-protection area (Fig. 3, 4; Nel *et al.* 2011). Although ecologically important, this WMA is also one of the most highly

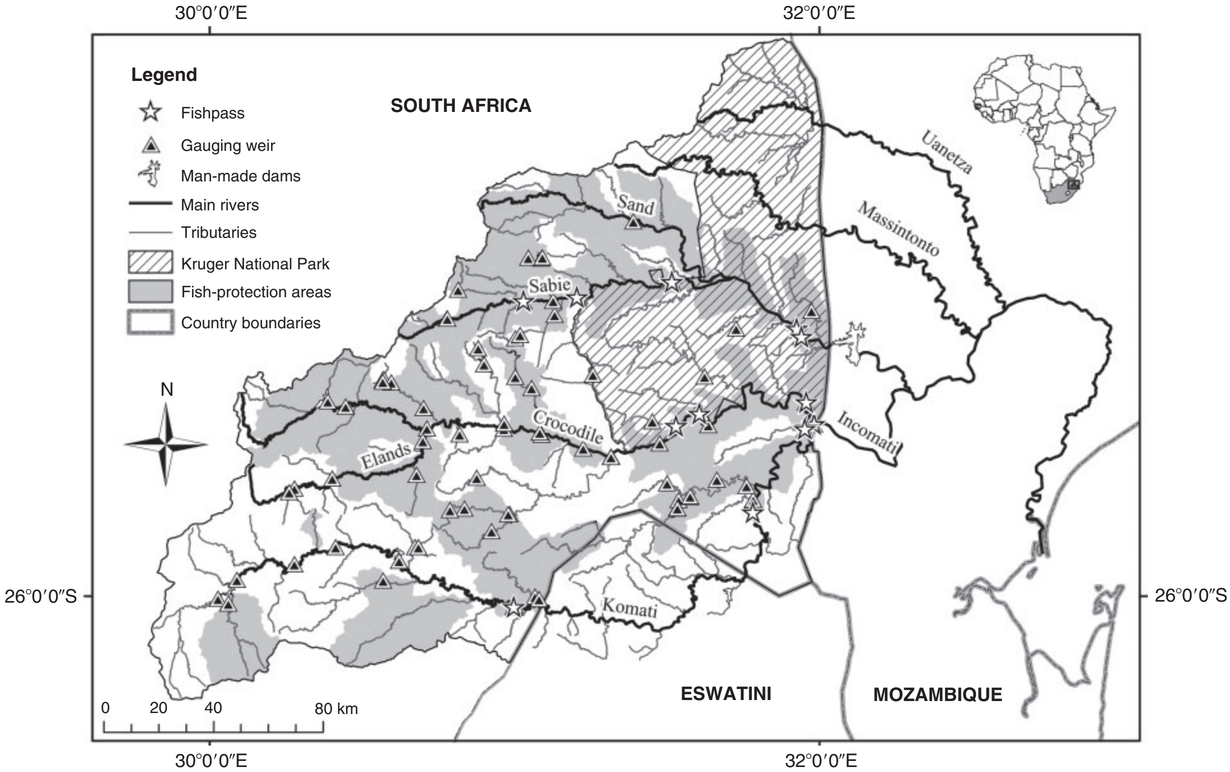

Fig. 4. Rivers, man-made lakes (dams) and gauging weirs in the Inkomati Water Management Area of South Africa, with fish-protection areas as a part of the Freshwater Ecosystem Priority Areas of South Africa (Nel *et al.* 2011) and fish passage facilities included.

stressed ecosystems in South Africa (Soko and Gyedu-Ababio 2015; Jackson *et al.* 2016). In the WMA, land-use transformation for agriculture and urbanisation is excessive primarily upstream of the Kruger National Park, one of the world's largest conservation areas (Fig. 3). Within the semi-arid WMA, 12 formal dams and >200 informal farm dams have been constructed. In addition, there are 83 formal gauging weirs and >10 causeways that all affect fish migrations (Fig. 3). However, only 12 fish passages (<1% of infrastructure development) have been established in the WMA, and many of these are non-functional (Bok *et al.* 2007; Silva *et al.* 2018). The synergistic effect of multiple land-use activity-derived stressors, affecting habitat, water quality and flows in the WMA, and disturbance to wildlife stressors, including alien invasive species and migration barriers may all be contributors to the significant reduction in the well-being of the fish communities of the WMA.

In 2016, a suite of RQOs was gazetted for the Inkomati Basin (*National Water Act* (36/1998): Classes of Water Resources and Resource Quality objectives for the Catchments of the Inkomati Notice number 40531 of Act number 1616 of 2016) to maintain the well-being of numerous fish communities in a range of ecological categories from pristine to largely modified conditions. The new legislation provides no requirements for river connectivity management that may be required to restore fish migrations to meet the RQOs.

The well-being of the three major rivers of the Inkomati basin, namely the Sabie, Crocodile and Komati rivers, varies because of connectivity and land-use-derived stressors between rivers. The ecological condition of the Crocodile River has deteriorated, as indicated by biomonitoring surveys between 1998 and 2017, and can be attributed to the increase in water use for irrigation and other uses (Du Plessis 2019; Roux *et al.* 2019). Flow is highly regulated, with evidence of reversed seasonality linked to out-of-season releases from Kwena Dam to supply bulk users and honour international agreements with Mozambique (Palmer *et al.* 2018). Extraction of water for irrigation demands has further contributed to the degradation of the main stem of the Crocodile River, especially the lower reaches (Saraiva Okello *et al.* 2015; Burnett *et al.* 2018). Water quality and flows downstream from the Elands–Crocodile confluence has deteriorated, affecting rheophilic and semirheophilic fishes and migratory species in particular (e.g. *Labeobarbus polylepis*, *Labeobarbus marequensis*, *Chiloglanis bifurcus* and *Chiloglanis paratus*; Kleynhans *et al.* 1992; O'Brien *et al.* 2014; Soko and Gyedu-Ababio 2015; Burnett *et al.* 2018). The flow reductions affect dilution and, as a result, poor water quality is widespread within the catchment, which is compounded by the multiple pollution sources from various land uses, such as wastewater treatment works, agricultural, forestry, industry, urban surface run-off and land fill associated with urban and rural centres (Soko and Gyedu-Ababio 2015). This has resulted in the Crocodile River being predominantly in the moderately modified ecological condition downstream of Kwena Dam (Soko and Gyedu-Ababio 2015).

The water quality of the Komati River is in fairly good condition, but increased water demands for irrigation, transboundary agreements and drought conditions are resulting in low- to no-flow periods that have never historically been observed (Du Plessis 2019). Three large dams (Nooitgedaght, Vygeboom and Maguga) are located on the main stem, with several gauging weirs downstream from Maguga Dam, augmenting and pooling instream habitat (Fig. 3). These weirs have been constructed primarily to provide water for sugarcane irrigation, with fishways on these weirs not considered or dysfunctional. Many migratory fishes, such as *Labeo rosae*, *Labeo congoro* and *Mesobola brevianalis*, previously recorded in 1966 and 1967 surveys have not been recorded in recent surveys in 2014 and 2018, highlighting concern for river connectivity (Kleynhans 1986; Roux *et al.* 2019).

In contrast, the Sabie River is presently one of South Africa's most pristine ecosystems that maintains a high diversity (~51 species; Scott *et al.* 2006; O'Brien *et al.* 2018*a*, 2018*b*) of fish representative of the Zambezian fauna that occurs in the Inkomati WMA (Kleynhans 1986; Skelton and Cambray 1995; Skelton 2001; Rivers-Moore *et al.* 2005). This has not historically been the case, whereby, in the late 1960s, because of upstream gold mining, the Sabie River was considered to be a wasteland and only able to maintain a small representation of the expected species (Pienaar 1978; Kleynhans 1986). In just over 10 years, between the closure of the mines in the 1970s and the construction of the Corumana Dam on the lower reaches of the Sabie River in 1983, the fish communities have been able to re-establish primarily through migrations from the Crocodile and Komati rivers (Roux *et al.* 2018). Presently, although some important catadromous migratory fishes (e.g. *Anguilla* spp.) are not expected to occur in the Sabie River, the well-being of populations of obligatory migratory species in the Sabie River are generally unknown. Without urgent attention, the suitability of the Sabie River to provide refuge for fishes, and associated ecosystem processes that are highly threatened in the rest of the WMA and surrounding WMAs, is uncertain. River connectivity and fish migration management appears to be a shortcoming of the management of multiple stressors in South Africa.

Good river connectivity and fish migration management practice have been established internationally and should be implemented in South Africa (Silva *et al.* 2018). This includes cooperation between multiple stakeholders of river connectivity management and fish migrations, and the formal integration of fish passage science into policy in South Africa. Available guidelines (Bok *et al.* 2007) provide direction to collect more information on species and river connectivity disruption mitigation measures, including good fish passage options. We urgently need to identify and prioritise existing migratory routes that are intact, and restore migratory routes for the protection of species in regions of high endemism and for species with conservation status. These requirements could easily be packaged as RQOs through formal RDM procedures. Finally, we need to formalise the role of fish migrations and river connectivity processes in RDM and evaluate the contribution of the management of these ecosystem components to the sustainability of ecosystems.

Concluding remarks

Although water resources management in South Africa has been recognised as being progressive, it must still be adaptable to meet the vision of the legislation and provide adequate protection measures to resources and ensure sustainability. Water resource use in South Africa is locally and internationally recognised as being excessive. The high prevalence of threatened ecosystems needs to be addressed urgently to achieve sustainability. The numerous land-use-derived stressors that are known to be negatively affecting ecosystem well-being need to be managed. Although RDM procedures that result in RQOs or targets to protect resources and the resulting legislated objectives or targets for resources are considered to be adequate for resource protection, there is presently very little consideration of the management of river connectivity and fish migrations. Today in the region we already have a new plethora of gazetted protection objectives or targets for major water resources. Implementation, and, importantly, consideration of river connectivity issues and fish migration, is lacking. Migratory fish in the region are socioecologically important and vulnerable to multiple anthropogenic stressors. The existing effort to mitigate river connectivity disruptions by the >2000 artificial barriers in South Africa with ~60 fish passage facilities is inadequate. River connectivity and fish migration management appear to be shortcomings of the existing management approach for multiple stressors, and a potential cause for the existing high diversity of threatened and endangered species and ecosystems in the region (Driver *et al.* 2012). Fish passage science in South Africa is currently undervalued and should be elevated to contribute to the national sustainability vision for water resources and become aligned with international fish passage science, engineering and practice.

Conflicts of interest

This work was developed through collaboration of the authors and their expertise in the research areas presented in the paper. The authors declare that they have no conflicts of interest.

Declaration of funding

The authors acknowledge the financial contribution from the National Research Foundation of South Africa through the BRICS Multilateral Joint Science and Technology Research Collaboration study titled, 'Global and local water quality monitoring by multimodal sensor systems' and the Community of Practice grant to the Centre for Functional Biodiversity, University of KwaZulu–Natal.

Acknowledgements

The authors acknowledge the valuable comments provided by the reviewers of the manuscript.

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Handling Editor: Daniel Deng

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