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Designing a conservation area network that supports the representation and persistence of freshwater biodiversity

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SUMMARY

1. The progression of approaches in systematic conservation planning from representation to representation and persistence has greatly enhanced its potential applicability to freshwaters. However, conceptual frameworks that consolidate principles for incorporating persistence into freshwater conservation planning are still lacking.
2. We present four key principles to consider when planning for the persistence of freshwater biodiversity: selecting ecosystems of high ecological integrity; incorporating connectivity; incorporating areas important to population persistence; and identifying additional natural processes that can be mapped.
3. The practicalities of gathering data and conducting the conservation plan to address these principles are explored here using a case study in the Olifants/Doorn Water Management Area, South Africa. Spatial layers are developed for depicting ecological integrity, sub-catchment boundaries, riparian zones and wetlands, high water-yield areas and patterns of groundwater discharge and recharge.
4. These data are used to develop a conservation area network that supports both representation and persistence of freshwater biodiversity. Although the planning region is relatively data rich by global standards, several data deficiencies were identified. We suggest ways of using environmental surrogates to address data deficiencies, improving confidence in these surrogates by combining them wherever possible with existing field data and expert knowledge.
5. We also recommend methods to achieve spatial efficiency by simultaneously designing for representation and persistence of freshwater biodiversity. Spatial efficiency can be achieved in different ways when using a conservation planning algorithm and a multiple-use zoning strategy.
6. The allocation of multiple-use zones aligns closely with the objectives of integrated water resources management and land use planning. Given the practicalities at local levels of planning, we recommend using multiple-use zones in the design phase, rather than merely at the end once the design is complete.

Keywords: connectivity, integrated water resources management, MARXAN, river, systematic conservation planning

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Introduction

Early efforts in systematic conservation planning focussed largely on representing biodiversity, such as species and ecosystem types, in an efficient set of protected areas (Kirkpatrick, 1983). This strong focus on representation in protected areas – where biodiversity is represented, bounded and protected – is not particularly useful for freshwater ecosystems. Given the connectivity of freshwater ecosystems, planning for the representation of biodiversity in isolated areas, without regard for upstream, downstream or upland areas, is conceptually flawed.

Even in terrestrial settings, the shortcomings of this approach have been recognised and augmented with approaches that deal explicitly with the dynamic nature of natural systems (see Pressey *et al.*, 2007 for review). Approaches that consider dynamic natural processes can be grouped under the term 'planning for persistence' (Cowling *et al.*, 1999). They originated from the realisation that many natural processes responsible for maintaining and generating biodiversity will not persist if they are not explicitly incorporated into spatial design. This is especially true for natural processes that operate across large areas or require special spatial configurations, such as seasonal migration across large areas (Balmford, Mace & Ginsberg, 1998; Cowling *et al.*, 1999; Pressey *et al.*, 2007). Conservation areas should thus be embedded into a conservation area network designed for both representation and persistence of biodiversity.

The progression of approaches in systematic conservation planning from representation to representation and persistence has greatly enhanced its potential applicability to planning for conservation of freshwater ecosystems. Several freshwater-specific frameworks have recently been developed for representation of biodiversity (Higgins *et al.*, 2005; Turak & Koop, 2008; Ausseil *et al.*, 2010), and the recent incorporation of longitudinal connectivity into conservation planning algorithms is a major advance in dealing with persistence (Linke *et al.*, 2007; Moilanen, Leathwick & Elith, 2008). However, conceptual frameworks that consolidate principles for explicitly incorporating persistence into freshwater conservation planning are still lacking. This article combines current approaches for freshwater biodiversity representation, emerging knowledge on planning for persistence in the terrestrial realm and concepts from freshwater ecology to develop and apply an approach for planning for representation and persistence in freshwater settings. The approach consists of three steps: (i) developing key principles for incorporating persistence into freshwater conservation planning, clarifying their basis and rationale; (ii) assembling data for including these principles in conservation planning; and (iii) the use of these data, along with data on representing freshwater biodiversity, to design a freshwater conservation area network for use within the context of integrated water resources management. The article is structured accordingly, using the Olifants/Doorn Water Management Area in South Africa as a case study.

Persistence principles

We have distilled four key principles to consider when planning for the persistence of freshwater biodiversity. The first two principles cater for a range of dynamic natural processes that are key drivers of the structure and functioning of most freshwater ecosystems. The remaining two principles target more specific aspects of persistence, where data are available. These principles are not new to the literature, being based either on freshwater ecological theory or concepts borrowed from terrestrial conservation planning. They should be applied throughout the conservation planning process and, importantly, are often used in conjunction with considerations of representation (Table 1). Incorporating each of the principles below enhances the adaptive capacity of freshwater systems to climate changes (Palmer *et al.*, 2008). However, beyond this study, further research is required around additional principles that explicitly examine persistence under climate change.

Principle 1: select systems of high ecological integrity

Ecological integrity is key to planning for the persistence of biodiversity. In its broadest sense, it can be defined as the undiminished ability of an ecosystem to continue its natural path of evolution, its normal transition over time and its successional recovery from disturbances (Westra *et al.*, 2000). In terrestrial conservation planning, ecological integrity is therefore used as a screening mechanism in planning for

Table 1 Steps used to design a conservation area network (modified from Gaston, Pressey & Margules, 2002), together with principles of persistence to be applied at each step

Typical stages in designing a conservation area network	Persistence principle to consider
Define planning units	Connectivity through the use of sub-catchments
Compile data on biodiversity, current impacts and future threats, existing conservation initiatives	Ecological integrity
Record the extent of intact or restorable biodiversity per planning unit	Ecological integrity
Set quantitative conservation targets	Population persistence in setting population sizes, core ranges and rules for replication
Spatial design for both representation and persistence, aligning with existing conservation initiatives	Longitudinal connectivity; vertical connectivity; fixed spatial components of processes
Incorporation of any remaining Critical Management Zones	Longitudinal connectivity; lateral connectivity within sub-catchment (e.g. riparian zones and associated wetlands)

representation, preferentially selecting ecosystems of high ecological integrity for representation (Groves, 2003), or where this is not possible selecting areas with best restoration potential. Whilst this principle is associated more with incidental capture of functional processes rather than targeting specific spatial requirements of processes, it is an important bridging theme between freshwater ecology and conservation planning. The concept of ecological integrity is well established in freshwater ecology (Boulton, 1999) and supports the notion that selecting freshwater systems of high ecological integrity captures a multitude of fine-scale biological processes (e.g. competition, predation and small-scale disturbance and recolonisation dynamics) as well as important physical and chemical processes that shape the structure and functioning of freshwater systems (Fig. 1).

Principle 2: incorporate connectivity

The persistence of most freshwater ecosystems is, directly or indirectly, maintained through connectivity along three spatial dimensions (longitudinal, lateral and vertical) and a temporal dimension linked to the availability, quality and quantity of surface water over time, with flow regimes being of crucial importance (Ward, 1989; Poff *et al.*, 1997; Pringle, 2001). These dimensions are interdependent, emphasising the importance of considering connectivity across all dimensions (Ward, 1989; Pringle, 2001; Ward & Tockner, 2001; Freeman, Pringle & Jackson, 2007). Longitudinal connectivity describes the upstream–downstream continuum of rivers (Vannote *et al.*, 1980), lateral connectivity refers to the interactive pathways from the river channel to the surrounding

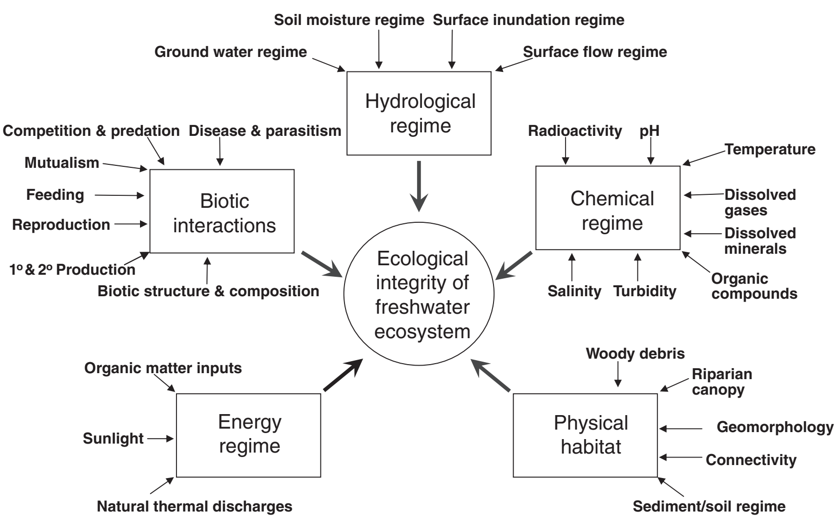

Fig. 1 The biological, physical and chemical processes thought to be key determinants of freshwater ecological integrity (modified from Karr *et al.*, 1986). An ecosystem is assumed to have a high ecological integrity when these determinants operate within their normal range of variation.

catchment (Naiman & Décamps, 1997) and vertical connectivity describes exchange between surface waters and ground water (Ward, 1998). The maintenance of connectivity along all spatial dimensions depends on the temporal dynamics of the natural flow regime (Pringle, 2001). For example, decreased flow, particularly at certain times of the year, can disrupt longitudinal and lateral connectivity and prevent free passage to spawning habitat (Ward & Tockner, 2001).

Principle 3: incorporate areas important to population persistence

Targeting systems with a high ecological integrity and incorporating connectivity into conservation design serve as generic surrogates for the persistence of populations in a conservation area network and will sometimes be the only ones available. As a further safeguard where data are available, this principle explicitly addresses the persistence of species selected for representation in a conservation plan. Considerations specific to the persistence of each species population include incorporating access to all critical habitat required over the lifetime of each species; identifying areas that serve as spatial refugia and incorporating linkages between these and the populations targeted for conservation; replication within the planning region in areas that are unlikely to be influenced by the same natural or human disturbances; and incorporating populations or metapopulations that are large enough to prevent extinction from random demographic and genetic events (Moyle & Yoshiyama, 1994).

Principle 4: incorporate additional natural processes that can be mapped

Incorporating ecological integrity and connectivity cater for maintaining generic natural processes that are key drivers of the majority of freshwater ecosystems. There may also be instances where other specific natural processes are key determinants of the structure and functioning of freshwater ecosystems and whose spatial components can be mapped. In conservation planning, these processes are referred to as 'fixed spatial components' (Rouget *et al*., 2006). Some of these fixed spatial components may already have been identified in the three previous principles, e.g. areas that depend strongly on ground water for maintaining spatial refugia may have been mapped in considering vertical connectivity. This principle addresses any additional fixed spatial components that may need incorporation. For example, high water-yield areas could be identified to highlight areas that are particularly important for maintaining natural flow regimes throughout entire catchments (Rivers-Moore, Goodman & Nel, 2010). Fixed spatial components are commonly defined using environmental surrogates such as climate, topography, geology, soils and vegetation.

Methods

We assembled data based on these persistence principles, along with data for representing biodiversity, to design a spatially efficient freshwater conservation area network for the Olifants/Doorn Water Management Area, South Africa (Fig. 2). The study was commissioned by the national Department of Water Affairs and Forestry to inform water resources planning in the region and hence had a strong focus on real-world application. The time frame for developing these data was rapid (only 2 months) but was greatly facilitated by the relatively comprehensive existing data and expert knowledge in the region. We harnessed this expert knowledge through individual consultations to collate available data and build consensus on how this information was to be used in the conservation plan and through a workshop where we brought together experts to debate and review the resulting spatial layers. All data were collated in the geographical information system (GIS), ArcGIS 9 (ESRI, 2002).

Study area

The Olifants/Doorn is one of the 19 water management areas in South Africa, within which integrated water resources management and catchment management plans will be developed (Fig. 3). It is a large area (approximately 56 750 km^2), situated on the west coast of the country, and incorporates the entire drainage area of the Olifants River system, of which the Doring River is a major tributary. Smaller coastal river systems north and south of the Olifants River estuary are also included in the planning region.

Coastal lowlands rise to rugged mountains at almost 2000 m above sea level, and climatic conditions differ considerably as a result of this variation in

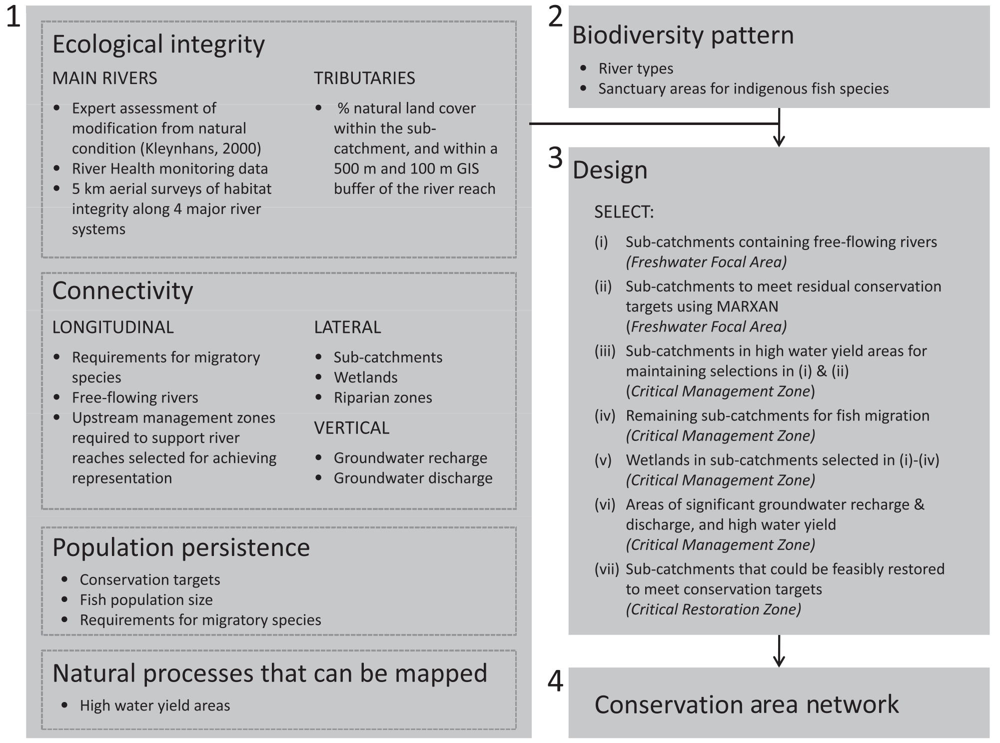

Fig. 2 Flowchart of steps used in the analysis showing the data gathered to address the four persistence principles (step 1), which were combined with data for representing biodiversity (step 2) and used to design a conservation area network (steps 3 and 4). The zones allocated to each of the selections in step 3 are shown in italics.

topography (DWAF, 2005a). Mean minimum temperatures in winter vary from −3 to 3 °C, whilst summer mean maximum temperatures range from 39 to 44 °C. This is a winter rainfall area, with mean annual rainfall varying between 100 and 1500 mm across the planning region. Gross mean annual evaporation is high (approximately 1500–2200 mm).

Although fish species richness is low, the region is a notable southern African endemic hotspot for freshwater fish (Skelton *et al.*, 1995). Nine of the 12 indigenous freshwater fish species are endemic to the planning region, and all are threatened (Table 2). Ground water plays a particularly important role in the region, sustaining river flow and refuge pools in the summer low flow periods (DWAF, 2005a). In addition, groundwater recharge in the region is believed to sustain coastal aquifers and groundwater-dependent ecosystems over 100 km away.

Main threats to the persistence of freshwater biodiversity in the planning region include over-abstraction of surface water and ground water for irrigation; degradation of wetland and riparian zones through grazing, bull-dozing and planting of crops; pollution from agricultural pesticides; and impacts associated with alien plant and fish species.

Biodiversity

Landscape- and species-level surrogates were used to represent river biodiversity (Fig. 2). Landscape-level surrogates for all 1 : 500 000 rivers in the planning region (DWAF, 2006) were derived by combining three levels of information: South African Level 2 ecoregions (Kleynhans, Thirion & Moolman, 2005), hydrological indices (Hannart & Hughes, 2003) and geomorphological river zones (Rowntree & Wadeson, 1999). Ecoregions broadly characterise the landscape through which a river flows, such that rivers in the same ecoregion share similar broad ecological characteristics compared to those in different ecoregions (Omernik, 1987). The hydrological index (HI) quantifies the amount and variability of natural water flow in a river and was used to distinguish three river flow regimes (Dollar, Dollar & Moolman, 2006): permanent ($HI \le 16.110$), seasonal ($16.110 < HI \le 37.819$) and ephemeral ($37.819 < HI \le 110$). The

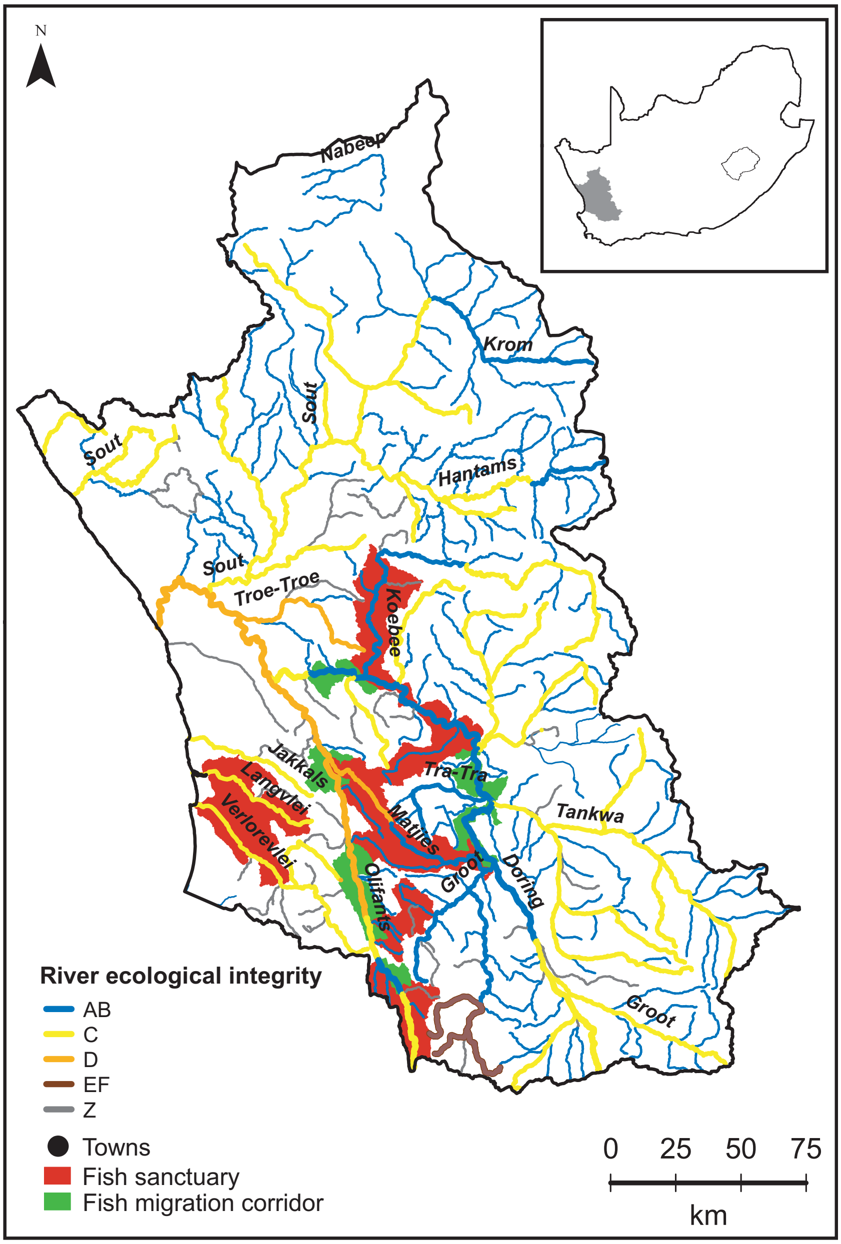

Fig. 3 Study area showing major towns and location in South Africa, as well as ecological integrity, fish sanctuaries and fish migration corridors associated with the 1 : 500 000 river network. Main rivers and tributaries are indicated, respectively, by thick and thin lines.

geomorphological river zones characterise the ability of each river reach to store or transport sediment, with each zone representing a different physical template available for the biota. Slope profiles were used to stratify the river channel according to the descriptions and slope categories proposed by Rowntree & Wadeson (1999), using techniques described by Moolman, Kleynhans & Thirion (2002). We grouped these into four classes for this study: mountain streams, upper foothills, lower foothills and lowland rivers.

We were not able to map wetland types confidently and therefore wetlands were excluded from consideration of biodiversity. However, wetlands were recognised for their functional role in the persistence of river biodiversity and were included in the consideration of lateral connectivity.

Very few comprehensive species-level data exist in the planning region, except for the 12 indigenous freshwater fish (Table 2). Fish point locality records from the South African Institute for Aquatic Biodiversity (SAIAB), Albany Museum and CapeNature were

Table 2 Freshwater fish species of the Olifants/Doorn

Common name	Scientific name	Conservation status
Verlorevlei redfin*	*Pseudobarbus burgi* (Boulenger, 1911)	Endangered
Fiery redfin*	*Pseudobarbus phlegethon* (Barnard, 1938)	Critically endangered
Clanwilliam redfin*	*Barbus calidus* (Barnard, 1938)	Vulnerable
Twee River redfin*	*Barbus erubescens* (Skelton, 1974)	Critically endangered
Clanwilliam sawfin*	*Barbus serra* (Peters, 1864)	Endangered
Clanwilliam yellowfish*	*Labeobarbus capensis* (Smith, 1841)	Vulnerable
Clanwilliam sandfish*	*Labeo seeberi* (Gilchrist & Thompson, 1911)	Endangered
Spotted rock catfish*	*Austroglanis barnardi* (Skelton, 1981)	Endangered
Clanwilliam rock catfish*	*Austroglanis gilli* (Barnard, 1943)	Vulnerable
Chubbyhead barb	*Barbus anoplus* (Weber, 1897)	Data deficient
Cape galaxias	*Galaxias zebratus* (Castelnau, 1861)	Data deficient
Cape kurper	*Sandelia capensis* (Cuvier, 1831)	Data deficient

Asterisks indicate species endemic to the planning region. Conservation status is based on a 2007 assessment (IUCN, 2007).

collated to produce a database of over 3000 localities. These data were refined using the population persistence principle to identify fish sanctuary areas.

Ecological integrity

Ecological integrity of the 1 : 500 000 rivers was mapped using existing data for main rivers in combination with a modelling approach for the smaller tributaries (Fig. 2). Main rivers were defined according to Nel *et al.* (2007) using the South African quaternary catchments (Midgley, Pitman & Middleton, 1994), which are nested hydrological units from primary catchments through to secondary and tertiary catchments and finally to quaternary catchments. Main rivers span more than one quaternary catchment, whilst tributaries are completely contained within single quaternary catchments.

We assigned ecological integrity to main rivers using the categories from Kleynhans (2000; Table 3). Rivers with an overall category A or B were considered 'intact'. Ecological integrity for main rivers was mapped using three existing datasets: (i) present ecological status (Kleynhans, 2000; Nel *et al.*, 2007) based on an expert-derived assessment of six criteria (flow, inundation, water quality, stream bed condition, introduced instream biota, riparian or stream bank condition); (ii) River Health Programme monitoring sites that use aquatic community and habitat indicators at a site level (River Health Programme, 2006); and (iii) aerial habitat integrity surveys at 5-km stretches along four rivers selected for environmental flow assessment (Brown *et al.*, 2006). Present ecological status was used as the primary GIS layer and updated where necessary according to the latter two datasets.

Table 3 Categories used to describe the current and desired future ecological integrity of South African rivers (after Kleynhans, 2000). We regard categories A and B as 'intact', with the ability to contribute towards conservation targets

Ecological integrity category	Description
A	Unmodified, natural
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem functions are still predominantly unchanged
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions have occurred
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions are extensive
F	Critically/extremely modified. Modifications have reached a critical level, and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances, the basic ecosystem functions have been destroyed and the changes are irreversible

Owing to a lack of comprehensive data, we derived ecological integrity for tributaries using the percentage of natural land cover as a surrogate. Remotely sensed land cover data are the most common surrogate measures used to infer information about the impact that human activities have on freshwater systems (Stein, Stein & Nix, 2002; Linke *et al*., 2007; Norris *et al*., 2007; Thieme *et al*., 2007), although still the subject of debate (Gergel *et al*., 2002; Allan, 2004). We defined natural and transformed land cover classes from the 30-m resolution South African National Land Cover 2000 GIS layer (Fairbanks, Thompson & Vink, 2000). Transformed land classes included cultivated, urban, degraded and eroded land, as well as plantations, mines and quarries. Farm dams at a 1 : 50 000 scale (Department of Land Affairs: Chief Directorate of Surveys and Mapping, 2005) were also used to distinguish natural from artificial waterbodies. The remaining land cover classes were considered natural. Only two categories of integrity were assigned to tributaries: 'intact' (equated to the A or B ecological integrity categories of main rivers), or 'not intact' (assigned to a category of Z). Four steps were used to model ecological integrity categories for each tributary river reach, defined as the portion of river between the 1 : 500 000 river confluences. First, the percentage of natural land cover was calculated for each river reach within its sub-catchment and within a 500-m and 100-m GIS buffer of the river reach. Second, the minimum of these three percentages was assigned to each reach. Third, any river reach with a minimum natural land cover of ≥ 80% was assumed to be 'intact' (i.e. ecological integrity category A or B); any river reach below this threshold was taken as 'not intact' (assigned an ecological integrity category of Z). This threshold was guided by comparisons of some of the site-assessment data with modelled outputs and expert knowledge. Finally, we accounted for the inaccuracy of the land cover data in detecting land degradation, which is a problem in the drier regions where subsistence grazing often causes disproportionate degradation to rivers, altering the riparian vegetation and causing bank erosion (Thompson *et al*., 2009). Any intact tributary with > 3% erosion within a 500-m GIS buffer of the river reach was downgraded to 'not intact'.

Connectivity

We assembled data to quantify longitudinal, lateral and vertical connectivity (Fig. 2). The temporal dimension of connectivity cannot be adequately captured on a map and is best addressed in the establishment of management guidelines for systems included in the final conservation area network.

Longitudinal connectivity. Three aspects of longitudinal connectivity were incorporated (Fig. 2): requirements for large migratory species, identification of free-flowing rivers and selection of upstream management zones required to support river reaches selected for achieving representation. We deal with the requirements for large migratory species in the section below on population persistence. For the second aspect, we defined a free-flowing river as an intact river, more than 100 km long, that flows undisturbed from its source to its mouth, either at the coast or at the confluence with a larger river, without encountering any dams, weirs or barrages and without being hemmed in by dykes or levees. This is similar to the WWF (2006) definition, but less stringent than that of Nilsson *et al.* (2005), which requires that mean annual flow has not been altered by more than 2%. The final aspect for incorporating longitudinal connectivity was included during the design of the conservation area network. However, recognising that it will be politically impossible (and not entirely necessary) to include all rivers upstream of a conservation area, an *a priori* rule was set to select only upstream areas that are the most critical for maintaining appropriate flows. In this way, all intact river reaches having their source in areas of high water-yield were considered critical to maintaining the present ecological integrity of downstream reaches.

Lateral connectivity. Lateral connectivity was broadly incorporated into conservation planning through modelling sub-catchments around each river segment in GIS (Arc Hydro, Version 1.1; ESRI, Redlands, CA, U.S.A.) using 90-m resolution digital elevation data (U.S. Shuttle Radar Topography Mission data; see http://srtm.usgs.gov/).

We also identified important functional zones within sub-catchments by delineating riparian zones and wetlands (Fig. 2). To map wetlands in the planning region, we combined three existing GIS layers: (i) the sensitive wetlands of the Western Cape Province (Shaw & de Villiers, 2001); (ii) 1 : 50 000 perennial and non-perennial pans (Department of Land Affairs: Chief Directorate of Surveys and Mapping, 2005); and (iii) delineations from the beta version of the national wetlands map (South African National Biodiversity Institute; see http://wetlands.sanbi.org), derived from 30-m satellite imagery applied in conjunction with topography and wetness potential models to enhance wetland detection (Thompson *et al*., 2002; Ewart-Smith *et al*., 2006).

Riparian zones have not been comprehensively mapped for all 1 : 500 000 rivers in the planning region. Owing to limited resources, we were unable to use aerial photography, satellite imagery or field surveys for this aspect of lateral connectivity (but see Goetz, 2006; Goetz, Gardiner & Viers, 2008). Instead, a buffer was applied to either side of all 1 : 500 000 rivers. The width of this buffer varied according to the geomorphological river zone. A buffer of 100 m was applied on either side of lower foothill and lowland river zones; whilst a 50-m buffer was used for the remaining zones. Buffer widths were based on expert experience regarding valley confinement and threat mitigation: lower foothills and lowland rivers are less confined and require wider buffers to mitigate the effects of agricultural practices (e.g. pesticide spraying). These river buffers were placed around all rivers selected for representation or upstream management during the design of the conservation area network, thus becoming an integral part of the conservation plan. Application of river buffers in this context is intended to emphasise the importance of particular riparian areas in the conservation area network and should not undermine the legal riparian buffer (32 m) that applies to all streams under the National Environmental Management Act (Act 107 of 1998).

Vertical connectivity. To identify areas most critical to maintaining seasonal refuge pools, a predictive modelling approach using environmental surrogates was applied to map the probability of ground water–surface water interaction (Conrad & Münch, 2006). This approach used six GIS layers believed to be the primary determinants of ground water–surface water interaction within the region (Table 4). Each of these layers was classified into values between 0 and 4, which described their likelihood of ground water–surface water interaction: absent, low, moderate, high and very high, respectively. A weighting was also applied to each GIS layer, depending on its significance to groundwater interaction and the confidence in the data (Conrad & Münch, 2006; Table 4). Class values were multiplied by the associated weights assigned to each of the GIS layers, and then all GIS layers were summed to derive a composite map representing the probability of ground water–surface water interaction. Probability scores were divided into three classes: high (scores > 9), medium (scores 5–9) and low (scores 0–4).

A map of groundwater recharge (mm per year) was derived from a nationally available GIS layer at a 1-km resolution (DWAF, 2005b) to identify areas critical for maintaining groundwater recharge. The method of determining groundwater recharge was based on the chloride mass balance (Lerner, Issar & Simmers, 1990), which applied a GIS model that replicates natural processes of direct groundwater recharge across the country, calibrated using known recharge values at several sites (DWAF, 2005b). This was used together with expert knowledge on the groundwater patterns in the region to map significant areas of groundwater recharge, which were included in the design of the conservation network.

Population persistence

Three issues of population persistence were considered in designating fish sanctuary areas for the 12 indigenous freshwater fish species of the region (Fig. 2). First, a relatively sound expert knowledge of the freshwater fish of the region allowed us to identify river reaches with the most suitable habitat and containing the largest populations for each species. Selection of these areas, hereafter fish sanctuaries, was guided by consideration of point locality records extracted from the aforementioned fish databases. Second, conservation targets stipulated that each species must be represented at least twice by populations that were chosen by experts preferably on different major river systems. Third, migration corridors were identified for species requiring free passage between tributary and mainstem habitat. Fish sanctuary areas and migration corridors were combined for all species to provide a summary map of the areas

Table 4 Geographical information system (GIS) data layers used to map probability of ground water–surface water interaction. After Conrad & Münch (2006)

GIS layer	Description	pc>Rationale for use	Weight
Groundwater response units	Units that have similar hydrogeological characteristics. Based on 1 : 1 000 000 geology	Units that depict boundaries between aquifer and non-aquifer geological formations. A significant change in permeability at these interfaces may result in ground water discharging to the surface. A high weight was assigned to this GIS layer, since geology plays a key role in groundwater characteristics	3
Groundwater levels	Interpolated surface of depth to groundwater (m), based on borehole data	Ground water–surface water interaction is likely to be highest in areas where groundwater levels are shallow (i.e. close to the surface). A low weight was assigned to this GIS layer because of the high uncertainty in the data	1
Springs	The position of known springs in the planning region (not potential springs)	Points of known groundwater discharge. Springs in this area are important, therefore this GIS layer received a high weight	3
Geological faults	The position of geological faults in the landscape. Based on 1 : 250 000 geological structures	Faults are often favourable flow paths for ground water, although there are many faults that are weathered and essentially sealed, with no associated groundwater presence or movement. For this study, it was assumed that all faults are water bearing and a high weight was assigned	3
Groundwater-dependent ecosystems	Probability of occurrence of groundwater-dependent ecosystems. Based on 1 : 250 000 vegetation groupings	Management of ground water in the immediate vicinity of these ecosystems is crucial. A moderate weight was applied to this GIS layer because of its coarse national scale	2
Groundwater contribution to baseflow	Based on monthly flow data at the scale of a quaternary catchment	This GIS layer is the most commonly used national indicator of ground water–surface water interactions. For much of the planning region, however, these data indicate no groundwater-fed baseflow, yet field experience indicates ground water is an important contributor to maintaining these systems during the dry season (pers. comm., C. Brown, 2006). The GIS layer was consequently assigned a low weight	1

required for representation and persistence of indigenous freshwater fish species of the region.

Additional natural processes that can be mapped

Owing to the steep rainfall gradient, relatively small catchment areas contribute significantly to the maintenance of the natural flow regime of the entire region. Areas of high water-yield have already been delineated in the planning region as mountain catchment areas under South Africa's Mountain Catchment Area Act (Act No. 63 of, 1970). We used these to highlight areas that play a critical role in maintaining flow regimes of the region (Fig. 2).

Conservation area network design

The conservation planning algorithm MARXAN (Ball & Possingham, 2000; Possingham, Ball & Andelman, 2000) was used to aid decisions regarding the design of a space-efficient conservation area network. MARXAN is a complementarity-based algorithm that uses a simulated annealing optimisation method to achieve conservation targets at least cost (Ball & Possingham, 2000).

Processing of data for MARXAN. Using sub-catchments as planning units and input GIS data on river ecological integrity, river types and fish sanctuaries, we quantified the extent of intact river types within each planning unit, as well as the presence/absence of a fish sanctuary and loaded these data into MARXAN. Conservation targets were 20% of the total length of each river type. For fish sanctuaries, the conservation target in MARXAN was 100% (fish sanctuaries had already been identified according to a conservation target of at least two populations per fish species, preferably on different river systems).

Because connectivity tends to be non-directional in terrestrial settings, the MARXAN boundary cost (quantified as the length of the boundary) is usually applied to all boundaries to favour connectivity. This needs to be refined for planning in freshwater settings to accommodate the longitudinal connectivity of lotic systems. We did this by applying a boundary cost only to those boundaries belonging to pass-through sub-catchments, defined as those sub-catchment boundaries that intersected a 1 : 500 000 river. All boundaries were assigned a uniform boundary cost of 200 (irrespective of length). This value was derived using a series of MARXAN scenarios to test the sensitivity of the selections to different boundary penalties: setting the boundary penalty too low produced a relatively scattered solution, whilst setting the boundary penalty too high resulted in the selection of many connected sub-catchments that did not contribute towards conservation targets (e.g. sub-catchments in which river systems were not intact).

A planning unit cost was also applied to each sub-catchment in MARXAN, so that where choices existed between sub-catchments with similar biodiversity features and spatial connectivity, preference would be given to sub-catchments (i) identified as important for fixed spatial components of processes or (ii) aligned to existing conservation initiatives. The former was defined as those where the extent of significant groundwater discharge and recharge areas and significant water-yield areas together was > 50% of the sub-catchment. The latter was defined as those where > 50% of the sub-catchment was either under formal protection (Reyers *et al.*, 2007) or had been identified by the local conservation authority (CapeNature) as a priority for land stewardship adjacent to existing protected areas. A uniform value was assigned to all sub-catchments as the baseline planning unit cost and then all sub-catchments qualifying under criteria (i) and (ii) were 'discounted' to less than this baseline value. These values were determined through a series of MARXAN scenarios to test sensitivity to varying the planning unit cost and associated discount.

Design protocol. Eight steps were then used to design a conservation area network for representation and persistence of freshwater biodiversity (Fig. 2):

1. Earmark all sub-catchments containing free-flowing river reaches prior to beginning MARXAN. This forces these sub-catchments to be included in the conservation area network.
2. Run MARXAN to select a spatially efficient configuration of sub-catchments that achieves the residual conservation targets for representation from step 1. Use the boundary penalty and planning unit costs determined from the sensitivity analyses.
3. Select remaining sub-catchments required to maintain downstream conservation areas selected in steps 1 and 2. In line with the rule to allow for some small-scale water resource development in the region, restrict selections to only those upstream areas in high water-yield areas identified for sustaining environmental flow regimes.
4. Select remaining sub-catchments required to support migration between fish sanctuaries.
5. Select all wetlands associated with sub-catchments selected in steps 1–4.
6. Select significant areas of groundwater discharge and recharge and high water-yield areas.
7. Where conservation targets could not be achieved in intact systems, assess feasibility of restoring appropriate river reaches, guided by expert-derived data available for the country at a quaternary catchment scale (Best Attainable Ecological Management Class; Kleynhans, 2000), as well as the judgement of river practitioners in the planning region.
8. Zone according to the hierarchical protection strategy in Table 5 (after Abell, Allan & Lehner, 2007): rivers and their associated buffers were allocated to Freshwater Focal Areas if their sub-catchments were selected in steps 1 and 2, Critical Management Zones if selected in steps 3–6, or Critical Restoration Zones if selected in step 7. All remaining areas identified in step 6 were assigned to a Critical Management Zone, and then all sub-catchments selected in steps 1–7 were flagged as Catchment Management Zones.

Results

Biodiversity and ecological integrity

The combination of 15 Level 2 ecoregions, three river flow regimes and four geomorphological river zones produced 78 distinct river types. In total, 34 sub-catchments were selected as fish sanctuaries (Fig. 3) to achieve conservation targets. Conservation targets for *Barbus erubescens* were lowered to one occurrence because it is a highly localised endemic that can only be represented in one system. Only 57% of rivers in the planning region are considered intact, with main

Table 5 Zones allocated to the spatial components comprising the Olifants/Doorn conservation area network. Zones are based on a hierarchical protection strategy for freshwaters in which Freshwater Focal Areas are embedded within Critical Management Zones, which in turn are embedded in Catchment Management Zones (Abell *et al*., 2007). Management of Freshwater Focal Areas is focussed largely on representation and is likely to be fairly restrictive, with diminishing restrictions in the latter two zones where the focus is largely on persistence

Zone	Spatial component*
Freshwater Focal Area	River reach and buffer selected for achieving conservation targets
	Free-flowing river reach
Critical Management Zone	Upstream river reach and buffer critical for supporting a downstream Freshwater Focal Area
	River reach and buffer required to support migration between fish sanctuaries
	Wetland supporting a Freshwater Focal Area
	Significant areas of ground water-surface water discharge
	Significant areas of groundwater recharge
	Significant water-yield area
Catchment Management Zone	Sub-catchment containing Freshwater Focal Areas and/or Critical Management Zones
Critical Restoration Zone	Sub-catchment where feasible restoration will result in improved achievement of river type conservation targets

*A river reach is defined as the portion of river between confluences of a 1 : 500 000 river; this is also the reach around which sub-catchments (planning units) are delineated.

rivers proportionally more impacted than tributaries (Fig. 3).

Connectivity

In terms of longitudinal connectivity, the Doring River is one of the few remaining large free-flowing rivers in South Africa. All intact western and eastern tributaries of the Olifants and Doring rivers, respectively, have their source in high water-yield areas (Fig. 4) and were thus flagged as potential upstream management zones that are critical in sustaining any downstream conservation areas selected on the Olifants and Doring rivers, as well as the Olifants estuary.

A total of 528 sub-catchments, averaging approximately 110 km^2 in size, were modelled as planning units. Just over 2500 wetlands were mapped for consideration of lateral zones of importance within sub-catchments, ranging in size from $< 1\ km^2$ to

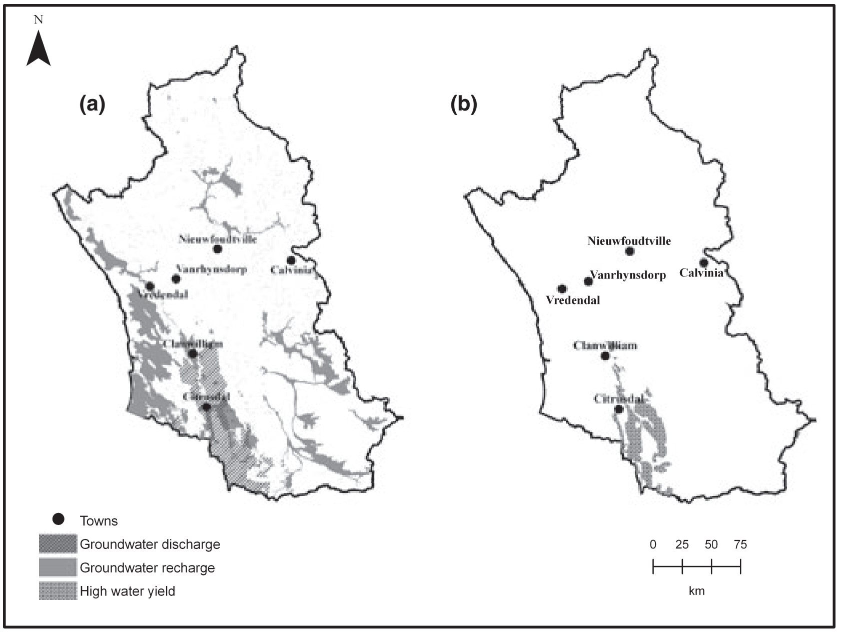

Fig. 4 Significant areas of (a) groundwater discharge and recharge and (b) water-yield in the planning region.

approximately 117 km^2, and totalling almost 530 km^2. The buffered river network within the conservation area network highlighted just over 690 km^2 of riparian zone that would need to be managed to maintain lateral linkages between the river channel and riparian zone.

Areas of high to medium likelihood of ground water–surface water interaction were considered to be significant areas of ground water discharge (Fig. 4a), totalling approximately 7600 km^2 (13% of the planning region). As with all data generated using surrogate information, these data have yet to be confirmed in the field. Areas where ground water recharge exceeds 30 mm per year were considered as having significant groundwater recharge in the South African context (DWAF, 2005b), totalling approximately 3350 km^2 (6% of the planning region; Fig. 4a).

Population persistence

In addition to the criteria for replication considered during fish sanctuary designation, 15 sub-catchments were identified as fish migration corridors between tributary and mainstem habitat of fish sanctuaries (Fig. 3). For many of the smaller-sized species, artificial barriers on river systems have actually served to protect tributary populations from predation by alien fish species prevalent in main rivers of the region. For such populations, barriers to longitudinal connectivity were retained by excluding connectivity of these tributaries with main rivers.

Additional natural processes that can be mapped

Areas of significant water-yield are associated with the high rainfall mountainous areas of the Cederberg and overlap to some extent (32%) with the significant areas of groundwater recharge (Fig. 4b).

Conservation area network design

Using the Abell *et al.* (2007) definitions, 74% of the Olifants/Doorn will be allocated to a Catchment Management Zone (Fig. 5), in which the land and water resources of the selected sub-catchments are afforded some level of conservation management. Only 1% of the Olifants/Doorn has been allocated to the highly restrictive Freshwater Focal Areas, with a further 19% to Critical Management Zones and 3% to Critical Restoration Zones (Fig. 5). Conserving all Freshwater Focal Areas will achieve conservation targets for all fish species and 72% of the river types. With feasible restoration of the Critical Restoration Zones (Fig. 5), 86% of the river types will meet their

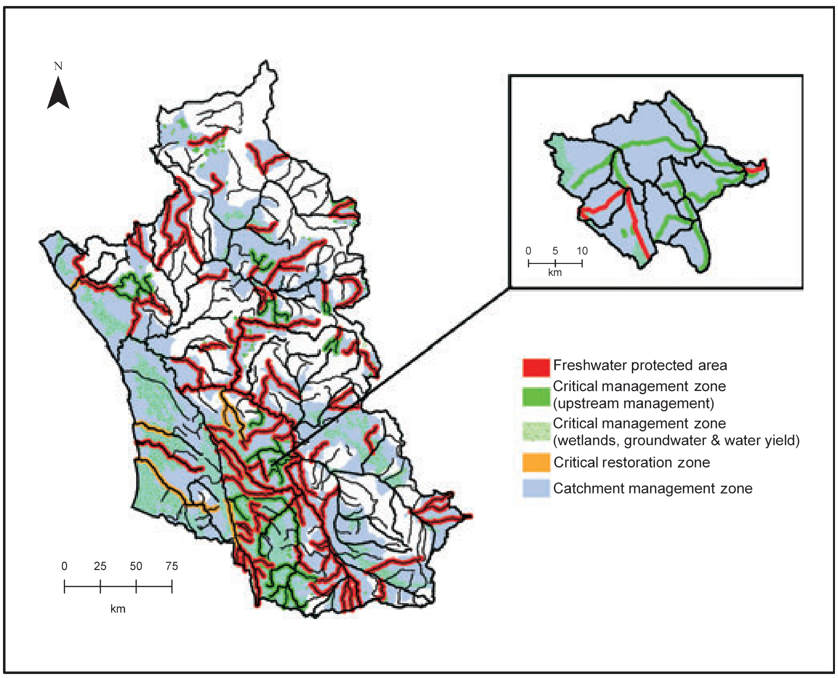

Fig. 5 Conservation area network designed to support representation and persistence of freshwater biodiversity in the Olifants/Doorn. Management zones are composed of spatial components listed in Table 5. The insert provides an example of the zones allocated within sub-catchments based on the different spatial components.

conservation targets in intact systems. It is not possible to fully achieve the conservation targets of the remaining river types, as restoring natural examples of these river types is not feasible in the planning region.

Discussion

The Olifants/Doorn Water Management Area, with its low human settlement and relatively intact ecosystems, offers good opportunities for conserving freshwater ecosystems. The Doring River is one of the largest free-flowing rivers in the country. Since options are extremely limited for conserving such rivers in South Africa, it should be regarded as a strategic national priority for conservation. In addition, this region is a hotspot for endemic fish, and the establishment, restoration and management of recommended fish sanctuaries should receive priority. Finally, the cumulative impact of small-scale abstraction of both surface water and ground water (particularly during the critical spawning season) needs to be addressed if biodiversity within the conservation areas is to persist in the long term. By mapping groundwater discharge and recharge patterns, and areas of high water-yield, the conservation area network highlights the areas most critical to begin this management.

This study set out to develop persistence principles and appropriate data to include these in conservation planning and to demonstrate how these data can be used, together with data on freshwater biodiversity, to design a freshwater conservation area network that could assist in water resources planning. Key findings in terms of data requirements for planning for persistence and conservation area network design are discussed below.

Data requirements

The persistence principles outlined in the introduction provide a good starting point for planning for the persistence of freshwater biodiversity. However, owing to lack of data in many planning regions, the application of this framework will rely on many assumptions. Even in the Olifants/Doorn Water Management Area, which is relatively data rich by global standards, we identified several data deficiencies (e.g. mapping ecological integrity of tributaries, delineating riparian zones and identifying significant areas of groundwater discharge). As an immediate solution, we suggested environmental surrogates to address these data deficiencies, improving confidence in these surrogates by combining them wherever possible with existing field data and expert knowledge. Longer-term empirical studies are needed to test the validity of these assumptions and improve guidelines for managing for the persistence of freshwater biodiversity. Emerging generalised dissimilarity modelling techniques recently used to classify rivers using biological data together with a series of environmental predictors holds good potential for improving the science of classifying freshwater ecosystems (Leathwick *et al.*, 2010).

A key research priority is to develop a better empirical basis for the use of thresholds in planning for persistence. This research could benefit conservation planning by developing a better basis for setting conservation targets based on species requirements and resilience considerations, testing the effectiveness of riparian and wetland buffer zones in maintaining ecological integrity of associated ecosystems and testing assumptions about thresholds in land cover and ecological integrity and their relationship on the persistence of freshwater biodiversity. These studies would be greatly assisted by extending the bioassessment and monitoring programme in the region (River Health Programme, 2006) into the areas selected within the conservation area network. In addition, studies examining thresholds in the flow requirements for freshwater species (e.g. flow velocities required during life cycles) would assist in developing operational guidelines for managing the temporal dimension of connectivity.

We dealt only with population persistence of freshwater fish. In terms of connectivity, this focuses attention mainly on requirements along the longitudinal dimension. Where information is available, expanding considerations to riparian or floodplain-dependent taxa would provide more detailed consideration of lateral connectivity. Incorporation of the vertical dimension of connectivity into freshwater conservation planning is a highly neglected topic of research (Linke, Turak & Nel, 2010). This study offers a first attempt at incorporating groundwater considerations from a persistence viewpoint, where areas most critical to maintaining seasonal refuge pools (areas of high ground water–surface water interaction) and areas responsible for the majority of groundwater recharge in the region are incorporated into the conservation area network as Critical Management Zones. These ideas should be developed and refined further, and a valuable opportunity exists to use this relatively data-rich, groundwater-dependent region for evaluating the performance of desktop techniques for mapping groundwater pattern and processes.

Conservation area network design

Planning for representation and persistence simultaneously. Applying the principles of persistence generates an array of rules and spatial data that will be used at different stages to design a spatially efficient conservation area network. It is clear that aspects of representation and persistence overlap (Table 1). Some persistence information will be incorporated before spatial design actually begins when formulating representation targets (e.g. fish population sizes and replication), developing ecological integrity filters (e.g. achieving conservation targets only in intact ecosystems) and defining planning units (e.g. using sub-catchments). Other persistence information will be accommodated during spatial design (e.g. where choices for representation exist, favour upstream or downstream sub-catchments or those containing fixed spatial components of processes). Finally, once complementary areas for representation and persistence have been selected, the design for connectivity can be completed (e.g. adding in remaining critical sub-catchments for maintaining longitudinal connectivity or allocating riparian buffers to selected river systems).

The spatial design process we have presented considers representation and persistence simultaneously to maximise efficiency of spatial design (Rouget *et al.*, 2006; Linke *et al.*, 2010). For example, where there is a choice of several sub-catchments to represent a specific biodiversity feature, a sub-catchment that contributes to as many other under-represented biodiversity features as possible is preferred. Sub-catchments that are needed to maintain connectivity or spatially fixed components of processes will also be given preference over isolated ones with similar biodiversity features.

Some persistence issues, such as longitudinal connectivity, depend on the location of areas for representing biodiversity. In this study, applying MARXAN's boundary penalty to pass-through sub-catchments aided the selection of connected sub-catchments whilst achieving conservation targets for biodiversity. Although this only achieved partial longitudinal connectivity, it permitted the allocation of multiple-use zones (*sensu* Abell *et al.*, 2007) because we were able to distinguish between sub-catchments required for achieving conservation targets (Freshwater Focal Areas) and those that were important for maintaining longitudinal connectivity, but not essential for achieving conservation targets (Critical Management Zones). If zones are not needed, an alternative method that allows simultaneous consideration of representation and connectivity is to use complementarity-based algorithms linked to rules that automate the selection of upstream and downstream linkages (Linke *et al.*, 2007; Moilanen *et al.*, 2008).

Spatial efficiency between areas chosen for representation and spatially fixed components of processes (e.g. free-flowing rivers, significant areas of groundwater discharge and recharge, or significant water-yield areas) should also be considered during planning for representation. This can be accomplished in two ways. One way is to force selection of these areas in the subsequent design by earmarking them prior to running the conservation planning algorithm (Rouget *et al.*, 2006). This is the method that we followed for sub-catchments associated with free-flowing rivers: targets for seven river types were immediately met through this action. Constraining selection in such a way inevitably results in a less spatially efficient design, but the benefits gained in managing persistence issues may make this a sensible compromise. However, it may not be worth compromising spatial efficiency if the spatially fixed persistence surrogates are to be zoned to incorporate less restrictive uses than those for representation. In this case, another method would be to favour these areas during planning for representation using the planning unit cost. Here, planning unit cost is traded off against the cost of spatial efficiency in representation, so that discounted planning units will be favoured where there are choices that result in similar spatial efficiency. This was the method we applied in the case of the significant areas of groundwater discharge and recharge, and significant water-yield areas.

In summary, when using a conservation planning algorithm, the manner in which spatial efficiency between persistence and representation is achieved depends on whether a multiple-use zoning strategy will be applied during design. Systematic conservation plans generally defer zoning to the implementation phase, although there are conservation planning algorithms, such as MARXAN with Zones, which explicitly acknowledge multiple-use zones during spatial design. Use of this algorithm in a freshwater context should be investigated.

Multiple-use zoning. Incorporating persistence criteria generally creates a space-hungry plan. To consider the advantage of using multiple-use zones imagine Fig. 5 as showing all zones as Freshwater Focal Areas. We believe that a multiple-use zoning strategy (e.g. Abell *et al.*, 2007) applied explicitly during the design of a conservation area network can facilitate implementation because (i) it makes the network more politically palatable in the context of water resources development; (ii) it strengthens the linkages between people and conservation; and (iii) it aligns more closely with planning categories used by water resource managers and land use planners.

The latter implies that implementation can be supported by relating the zones to existing land use and water resource planning categories (Knight, Cowling & Campbell, 2006). This study was undertaken with the specific goal of informing water resources planning in the region. In making water resource decisions, water resource planners attempt to balance human and ecosystem needs by examining scenarios of desired future condition of rivers (much like the ecological integrity categories in Table 3). Preparing a freshwater conservation plan, and preferably relating the zones to broad categories of desired future condition at a sub-catchment level, provides an explicit point of departure from which to negotiate the needs of freshwater biodiversity during this process.

In addition, the explicit and systematic inclusion of freshwater biodiversity into existing land use planning in the region can be achieved by relating the multiple-use zones of Fig. 5 to planning categories relevant to such initiatives. Land use planning initiatives complement existing water resources planning in the area by focussing on land management within the conservation area network. Here, delineations of multiple-use zones within the sub-catchment, such as wetlands, riparian and groundwater zones (Fig. 5), are particularly pertinent.

Using a multiple-use zoning strategy only provides a starting point for assigning levels of protection. These zones need to be refined to incorporate management guidelines that address site- and region-specific threats and overall sensitivity of the associated biodiversity to these threats.

Conclusions

This study shows that planning for representation and persistence in the freshwater domain is feasible through careful consideration of persistence principles, data, surrogates and zoning. To further support the effective implementation of this conservation plan, the entire exercise needs to be nested within a larger social process of stakeholder engagement that evolves over time, fostering a spirit of cooperation, alignment of mandates, co-learning and adaptive management. The formation of catchment management forums within the water management area under South Africa's Water Act (Act 36 of 1998), along with the imminent development of a catchment management strategy for the region, offers an ideal vehicle for mainstreaming a conservation vision into water resource management of the Olifants/Doorn Water Management Area.

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