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Expanding protected areas beyond their terrestrial comfort zone: Identifying spatial options for river conservation

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ABSTRACT

There has been very little consideration of freshwater ecosystems in identifying and designing protected areas. Recent studies suggest that protected areas hold enormous potential to conserve freshwater biodiversity if augmented with appropriate planning and management strategies. Recognizing this need, South Africa's relevant government authority commissioned a spatial assessment to inform their national protected area expansion strategy. This study presents the freshwater component of the spatial assessment, aimed at identifying focus areas for expanding the national protected area system for the benefit of river biodiversity. Conservation objectives to guide the assessment aimed to improve representation of river biodiversity pattern and processes in both new and existing protected areas. Data to address these objectives were collated in a Geographic Information System (GIS) and a conservation planning algorithm was used as a means of integrating the multiple objectives in a spatially efficient manner. Representation of biodiversity pattern was based on achieving conservation targets for 222 river types and 47 freshwater fish endemic to South Africa. Options were also identified for representing coarse-scale biodiversity processes associated with free-flowing rivers and catchment-estuarine linkages. River reaches that, with only minor expansion of existing protected area boundaries, could be fully incorporated into the national protected area system were also identified. Based on this study, generic recommendations are made on how to locate, design and manage protected areas for river biodiversity: use appropriate planning units, incorporate both biodiversity pattern and process, improve planning and management of individual protected areas, incorporate a mixture of protection strategies, and embed planning into an ongoing research and implementation process.

1. Introduction

Around the world, governments have made commitments to establish protected area systems that contain viable representations of every terrestrial, freshwater and marine ecosystem (IUCN, 2003). However, several recent studies worldwide have highlighted significant gaps in protected area systems for freshwater ecosystems, both in terms of their representation and their ecological viability and integrity (Keith, 2000; Yip et al., 2004; Abellán et al., 2007; Nel et al., 2007).

There are at least three reasons for this. First, there has been very little emphasis on freshwater ecosystems in identifying and designing protected areas – they are generally only protected incidentally through their incorporation into terrestrial protected areas (Saunders et al., 2002). Second, protected area management has focussed largely on managing terrestrial biodiversity – in many instances freshwater ecosystems within protected areas have even been deliberately altered by the construction of dams, roads, bridges and tourist lodges (Gaylard et al., 2003). Third, partial inclusion of rivers in protected areas is no guarantee for their protection since impacts outside protected area boundaries can still have negative consequences for freshwater biodiversity within them (Mancini et al., 2005). This means that protected area management plans need to acknowledge processes and threats external to their boundaries.

Consistent with the international trend, South Africa's system of protected areas shows significant gaps in conserving freshwater ecosystems. A recent systematic conservation assessment in South Africa (Nel et al., 2007) examined endangerment and protection levels of ecosystems associated with large rivers and found that: (1) less than 15% of these river ecosystems can be considered moderately to well represented within protected areas; (2) based on their present ecological status category (Kleynhans, 2000; Table 1), almost half of the large river systems that are incorporated into protected areas are not intact, having been degraded by upstream human activities before entering the protected

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Table 1
Present ecological status categories describing the extent to which the ecological integrity of a river has been modified by human activity (Kleynhans, 2000). The percentage of main river length, after Nel et al. (2007), is shown for each category. Rivers are considered intact if in an A or B category, moderately modified if in a C category and largely modified if in D–F categories.

Present ecological status category	Description from Kleynhans (2000)	% Main river length
A	Natural, unmodified	4
B	Largely natural	25
C	Moderately modified	48
D	Largely modified	21
E–F	Seriously to critically modified	2

area and (3) half of the river systems associated with protected areas are used to delineate boundaries and therefore only enjoy the benefit of protected area management on one side of their banks, if at all.

An important and more optimistic finding stemming from this study was that national data on present ecological status of rivers (Table 1) showed a higher proportion of intact river systems in protected areas (50%) compared to those outside (28%). This emphasizes the positive role protected areas can play in conserving freshwater ecosystems and associated biota. However, improving the role of protected areas in conserving freshwater ecosystems will require explicit incorporation of freshwater biodiversity into both protected area planning and management (Roux et al., 2008a).

In South Africa, the opportunity arose to incorporate freshwater biodiversity into spatial planning for protected areas when the national Department of Environmental Affairs and Tourism (DEAT) commissioned the development of a strategy to guide the expansion of the country's land-based protected area system – including both the establishment of new protected areas and expansion of existing ones. As input into the strategy, a spatial assessment of both terrestrial and freshwater biodiversity was undertaken to identify focus areas for expanding the protected area system for the benefit of both realms. This study presents the freshwater component, focussing on rivers as an initial step, with a view to expanding to a broader suite of freshwater ecosystems over time. We begin by outlining multiple conservation objectives to guide such analyses, and demonstrate how these objectives can be tackled and integrated using a systematic conservation planning algorithm. Generic recommendations are then made regarding how to locate, design and manage land-based protected areas so as to improve the potential of protected area systems for river biodiversity.

2. Methods

The approach to identifying focus areas for expanding South Africa's protected area system can be summarized into four stages (Fig. 1) that are similar to conservation planning approaches developed in the terrestrial realm (Margules and Pressey, 2000). Table 2 describes existing data that were used to derive the information needed to address the following steps within each stage.

2.1. Develop conservation objectives

Conservation objectives guiding this assessment included the representation of river biodiversity pattern (e.g. river types and fish species) and processes (e.g. free-flowing rivers) in both new and existing protected areas. In addition, strategic opportunities were identified for improving the persistence of river biodiversity through minor expansion of existing protected areas (Table 3).

River types describe components of rivers which, under natural conditions, are likely to share similar biological response potential, and can therefore be used as coarse-filter surrogates of river biodiversity pattern (Hunter, 1991; Higgins et al., 2005). River types were supplemented with species presence/absence data on freshwater fish endemic to South Africa, where freshwater fish were defined according to their tolerance or intolerance of brackish water (Skelton et al., 1995). These fish species served as a fine-filter surrogate of river biodiversity pattern (Hunter, 1991), and were included because they are often the species that fall through the coarse-filter net (Lombard et al., 2003), and loss of these species would be globally significant. Comprehensive species data do not exist at a national level for other freshwater taxa such as aquatic invertebrates, a limitation to which we return in addressing ongoing research and implementation.

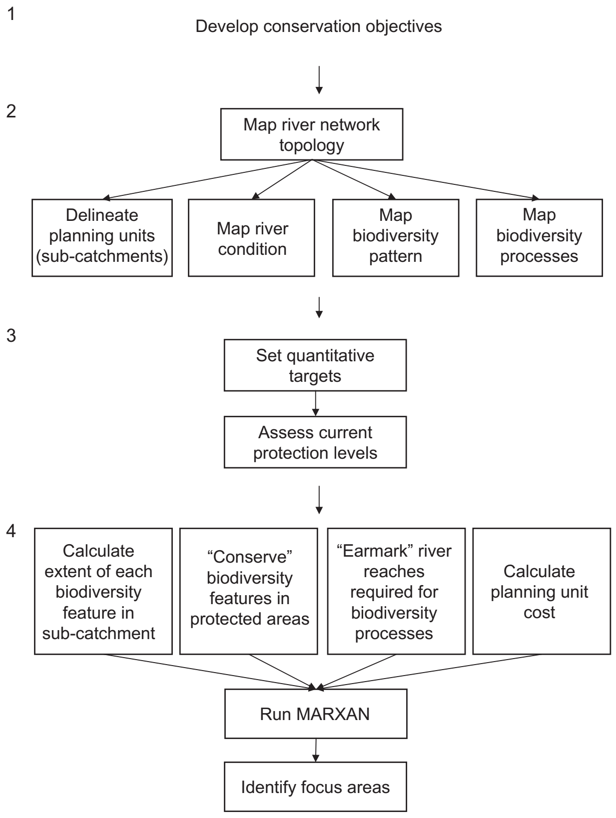

Fig. 1. Flowchart of steps used to identify freshwater focus areas for expanding the national protected area system. These steps can be summarized into four stages, similar to those used in terrestrial conservation planning (Margules and Pressey, 2000): (1) develop conservation objectives to guide the assessment; (2) collate data on the planning region; (3) assess current protection levels and (4) derive focus areas.

Two issues were considered in terms of representing biodiversity processes (Table 3): representing the last remaining free-flowing rivers, and representing linkages between intact river systems and priority estuaries. A third related issue, that of improving the persistence of river biodiversity in existing protected areas, focussed on identifying opportunities where minimal expansion of existing protected area boundaries would enable the full incorporation of river reaches that are currently only partially protected. This objective addresses the issue of improving longitudinal connectivity of rivers in protected areas, focusing on protection of the upstream–downstream continuum of river systems (Pringle, 2001).

2.2. River network and sub-catchments

This study was based on the 1:500,000 rivers Geographic Information System (GIS) layer within the boundaries of South Africa, Lesotho and Swaziland (DWAF, 2006; Table 2). Because available data on river condition exist for main rivers only (Kleynhans,

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Table 2
An overview of existing data used in this study, listing resolution, date, source and the subsequent data derived to inform the identification of freshwater focus areas.

Existing data	Scale/resolution	Date	Source	Data derived
River network	1:500,000	2007	DWAF (2006)	Sub-catchments, river types, river condition, free-flowing rivers, intact catchment-estuarine linkages, river reaches for incorporation into protected areas with minor expansion
Digital elevation	90 m	2003	United States Geological Survey (2003)	Sub-catchments
National Present Ecological Status	Quaternary catchment-scale (mean size 650 km^2)	1999	Kleynhans (2000)	Condition of main rivers
National Land Cover	30 m	2000	Fairbanks et al. (2002)	Condition of tributaries
National Level 1 Ecoregions	1:500,000	2004	Kleynhans et al. (2005)	River types
Flow variability	1:50,000	2005	Department of Land Affairs (2005)	River types
Geomorphological zones	1:500,000	2007	Moolman et al. (2002)	River types
National fish database	Point data	2007	South African Institute of Aquatic Biodiversity and Albany Museum	Endemic fish
Farm dams	1:50,000	2005	Department of Land Affairs (2005)	Free-flowing rivers
Temperate estuaries of Eastern and Western Cape Provinces	Point data	2007	Turpie and Clark (2007); scenario B5	Priority estuaries for catchment-estuarine processes
Subtropical estuaries of Eastern Cape Province	Point data	2005	Turpie (2005)	Priority estuaries for catchment-estuarine processes
Subtropical estuaries KwaZulu-Natal Province	Point data	2008	Rivers-Moore et al. (in review)	Priority estuaries for catchment-estuarine processes
National Protected Areas	1:250,000	2004	Driver et al. (2005)	River reaches for incorporation into protected areas with minor expansion; current protection levels; planning unit cost

Table 3
Conservation objectives used to guide identification of freshwater focus areas for expanding the national protected area system.

Objective	Rationale
1. Improve overall representation of river types and freshwater fish species endemic to South Africa, particularly threatened river types	River types and freshwater fish species serve as a coarse-fine surrogate approach to conserving representative examples of river biodiversity in South Africa. Threatened river types are particularly targeted since limited options remain for their conservation. Here, threatened river types are defined using the endangerment categories of Nel et al. (2007), which are based on the proportion of total length of that river type still intact
2. Select intact river systems	These systems are the ones that are most likely to support biodiversity features likely to persist in the long term
3. Promote new protected areas for conserving the remaining free-flowing rivers	Conserves representative coarse-scale processes such as natural flow regimes, erosion and sediment transport. There are very few free-flowing rivers left in South Africa
4. Represent intact rivers connected to priority estuaries	Conserves representative examples of catchment-scale processes that link land, water and sea
5. Identify ecologically functional river reaches that could be fully incorporated into a protected area with only minor expansion	Highlights potential opportunities for strengthening the persistence of rivers in existing protected areas. These opportunities should be investigated further in terms of practical and ecological feasibility

2000), we distinguished between 1:500,000 main rivers and tributaries. Main rivers are defined according to Nel et al. (2007) using the South African quaternary catchments, which are nested hydrological units within primary, secondary and tertiary catchments (Midgley et al., 1994). Main rivers span more than one quaternary catchment, while tributaries are completely contained within single quaternary catchments.

The 1:500,000 rivers GIS layer also includes a river network topology, where river segments between confluences are assigned a unique identifier that allows rivers upstream and downstream to be identified and grouped. We used this topology for GIS analyses of representation and persistence. In considering representation of biodiversity pattern, the assessment was conducted at the scale of a *river segment*, defined as the portion of river between confluences of the 1:500,000 rivers GIS layer (Fig. 2). For considerations of longitudinal connectivity and persistence, assessments were undertaken at the scale of a 1:500,000 *river reach*, defined as a whole river sub-system from its headwaters to either the estuary or confluence with a major river (Fig. 2). A river reach can be made up of several river segments, and may be relatively short or as long as, e.g. the Gariep River (almost 2000 km).

Sub-catchments were used as planning units in deriving spatial focus areas for expanding the protected area system. A total of 8548 sub-catchments, averaging 170 km^2 in size, were modelled around each river segment in GIS (Arc Hydro, Version 1.1, ESRI, Redlands, CA) using 90 m resolution digital elevation data (United States Geological Survey, 2003; Table 2).

2.3. River condition

Condition for all 1:500,000 rivers was assessed according to the extent to which the ecological integrity of a river has been modi-

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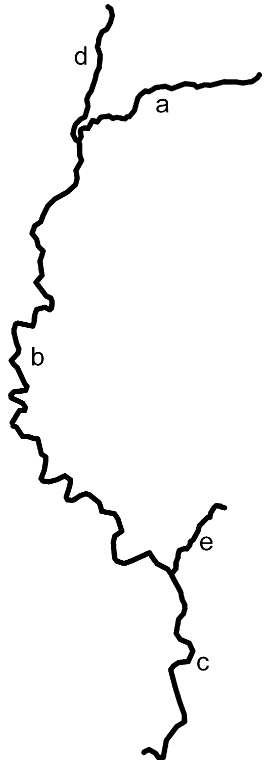

Fig. 2. Difference between river segments and river reaches. Five river segments are shown between river confluences, labelled a–e. These make up three river reaches – one comprised of multiple river segments a–c; and the remaining represented by d and e. Sub-catchments were delineated around each river segment.

fied by human activity, where ecological integrity was defined according to Westra et al. (2000) 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. We combined existing present ecological status categories for main rivers (Kleynhans, 2000; Table 1) with modelled categories for tributaries (Table 2). The latter used the percentage of natural land cover from the 30 m resolution National Land Cover 2000 GIS layer (Fairbanks et al., 2000) as a surrogate for river condition. This is based on studies that suggest that where no direct data exist, land cover can be used to infer information about factors that impact ecological integrity of freshwaters (Allan, 2004; Linke et al., 2007).

Present ecological status categories for main rivers range from A to F (Table 1; Kleynhans, 2000), and were collected through a series of sub-national workshops with river scientists and practitioners throughout the country between 1998 and 1999. The categories are based on an expert assessment of the modification of six attributes from their natural condition (flow, inundation, water quality, stream bed condition, introduced instream biota, riparian or stream bank condition), and were informed by existing data where possible. For this study, rivers were considered intact if in an A or B categories, moderately modified if in a C category, and largely modified if in D–F categories. Tributaries were considered intact if the minimum value for the percentage of natural land cover within the sub-catchment, 500 m and 100 m buffer of a river segment was $\geqslant$75% and percentage erosion within a 500 m buffer of a river segment was $\leqslant$5%; remaining tributaries were regarded as not intact. Elevating the impact of erosion was considered important in accounting for the inaccuracy of the land cover data in detecting land degradation (Thompson et al., in press).

2.4. Biodiversity pattern

Three GIS layers were combined to derive river types for the 1:500,000 river network (Table 2). First, each river segment was classified according to the majority Level 1 ecoregion (Kleynhans et al., 2005) through which it flowed. These river ecoregions characterise regions within which there is relative similarity in the mosaic of ecosystems and ecosystem components (biotic and abiotic, aquatic and terrestrial). Next, river flow variability was described as either "permanent" or "not permanent" using 1:50,000 topographical maps (Department of Land Affairs, 2005), where "permanent" groups perennial and seasonal rivers and "not permanent" refers to ephemeral rivers. The third GIS layer consisted of geomorphological zones derived for all 1:500,000 river channels (Moolman et al., 2002) using descriptions and slope categories proposed by Rowntree and Wadeson (1999). The seven geomorphological zones thus identified were grouped into four ecological classes: mountain streams, upper foothills, lower foothills and lowland rivers.

Presence/absence records for 47 endemic freshwater fish species, dating back to the 1940s, were extracted from the South African Institute of Aquatic Biodiversity (SAIAB) and Albany Museum fish databases (Table 2). To minimize the risk of selecting sub-catchments containing vagrant or erroneous data records, a sub-catchment needed at least two presence/absence records of differing collection dates to be considered suitable for achieving fish conservation targets.

2.5. Biodiversity processes

River reaches satisfying all of the following requirements were selected as free-flowing rivers: (1) permanent or seasonally flowing; (2) intact; (3) no instream dam throughout its length and (4) length $\geqslant$50 km for inland rivers, with no size threshold for coastal rivers. River types and river condition were used to identify reaches qualifying under (1) and (2), respectively. We used 1:50,000 farm dams (Department of Land Affairs, 2005; Table 2) to identify instream dams. To account for spatial inaccuracies between the 1:500,000 rivers and the 1:50,000 dams, the dams were buffered by 50 m. Any buffered dam that intersected a river was then assumed to be an instream dam.

We derived a single set of priority estuaries for South Africa from three estuarine systematic conservation plans (Turpie, 2005; Turpie and Clark, 2007; Rivers-Moore et al., in review; Table 2) that together covered the entire coastline of South Africa. Results from Turpie and Clark (2007) were used in instances where the planning domains of the former two studies overlapped. Using this single set of priority estuaries, we identified intact rivers attached to priority estuaries.

River reaches that could be fully incorporated into protected areas with only minor expansion were considered strategic opportunities to be investigated in terms of expanding existing protected areas. The focus here is on maintaining longitudinal connectivity (Pringle, 2001), rather than on representation in intact river systems. Non-intact river systems can still play an important role in maintaining longitudinal connectivity, e.g. moderately modified rivers can serve as fish migration corridors as long as they are managed appropriately (Abell et al., 2007). We therefore applied a less stringent rule for river condition by considering both intact and moderately modified main river systems and all tributaries regardless of their intactness. We made use of the national protected areas GIS layer (Driver et al., 2005; Table 2), defining formal protected areas as all national parks, provincial nature reserves, local authority nature reserves, DWAF Forest Nature Reserves, and Mountain Catchment Areas. River reaches that were already fully incorporated into formal protected areas were excluded from the

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analyses. To qualify further under this objective, the proportion of each river reach within (1) formal protected areas and (2) within a 2 km distance of formal protected areas was calculated. The latter criterion caters for river reaches falling on the boundary, or in the close vicinity, of protected areas. River reaches qualified if the proportion within (1) or (2) was ⩾50% or ⩾75%, respectively.

2.6. Setting quantitative conservation targets for representation of biodiversity pattern

For river types, we used a conservation target of 20% of the total length of each river type. This 20% target is a value endorsed by key government departments responsible for conserving freshwater ecosystems in South Africa (Roux et al., 2008b). However, it is acknowledged that this is an over-simplified measure that should be refined as better empirical data and methods for target setting become available. For fish, the conservation target was to incorporate at least one occurrence of each endemic fish species in protected areas, recognizing that this target should be supplemented with off-reserve conservation targets that incorporate a suitable level of resilience to natural and anthropogenic disturbances.

Only river types and fish records considered to have the ability to persist in the long term were able to contribute to achievement of conservation targets. Data on river condition were used for assessing the long term persistence of river types – only river types in intact systems contributed to conservation targets (Groves, 2003). Conservation targets for 55 river types (almost 25%) could not be achieved in intact rivers. Representation of these river types was not considered further in this study, but should be seen as a priority for investigation in terms of restoration.

In the absence of data for informing a detailed population viability analysis (see Margules and Sarkar, 2007) we relied mainly on river condition to assess the long term persistence of fish populations – only sub-catchments containing a minimum of 5 km of intact river length were considered suitable for achieving fish conservation targets. Using this criterion, four endemic fish species could not meet their conservation target. For these species, choices were few enough to add in sub-catchments representing the next best options, selected either from main rivers which could be feasibly restored, or from tributaries that had the highest percentage natural land cover modelled from the assessment of river condition. In the case of the former, we used national data on the best attainable ecological management category of main rivers (Kleynhans, 2000), which is an estimate (ranging from A to F; Table 1) derived by the same experts that derived data used for main river condition.

2.7. Assessing current protection levels

Current protection levels were assessed by examining the contribution made to conservation targets by river types and endemic fish currently within formal protected areas. Based on categories from Nel et al. (2007), well-protected river types were defined as those with ⩾100% of their conservation target conserved in protected areas; similarly, moderately protected, poorly protected and hardly protected river types have at least 50%, 5% and ⩾0% of their target conserved, respectively. To assess protection levels of endemic fish within protected areas, we investigated species records that were within formal protected areas and considered likely to persist in the long term. Fish species were described either as protected or not protected, depending on whether or not such a record existed for that species.

2.8. Deriving focus areas

The Marxan conservation planning algorithm was used as a means of integrating the multiple objectives of this study (Table 3). Marxan uses a simulated annealing optimization method to identify priority areas that meet conservation targets while minimizing costs (Ball and Possingham, 2000; Possingham et al., 2000). Marxan executes a user-specified number of runs, calculating alternative sets of priority areas (or "portfolios") for achieving conservation targets with each run: the best portfolio is the one with the lowest cost. The number of times a planning unit is selected in each run is also calculated and this frequency of selection serves as an estimate of irreplaceability (Ferrier et al., 2000): planning units selected in every run are irreplaceable as no options exist for their replacement; while planning units with lower irreplaceability can be replaced by other ones.

For each sub-catchment, the extent of each biodiversity feature (river type length, fish presence/absence) contributing to conservation targets was quantified. These, together with the respective conservation targets for each river type and fish species were loaded into Marxan.

The contribution made to conservation targets by existing formal protected areas was acknowledged for both river types and fish species in our Marxan analyses. This was achieved by flagging all river types and fish species that contribute to conservation targets inside formal protected areas as "Conserved" before beginning the Marxan runs.

Sub-catchments considered of strategic importance for biodiversity processes were flagged as "Earmarked" prior to the Marxan runs. Earmarking planning units is a means of forcing their selection in the final Marxan output. These included sub-catchments containing free-flowing rivers, river reaches that could be fully incorporated into a protected area with only minor expansion, or intact rivers linked to priority estuaries.

Assigning a planning unit cost is one of the methods used by Marxan to meet conservation targets while minimizing costs (Ball and Possingham, 2000; Possingham et al., 2000). This cost can be expressed as area of the planning unit, monetary cost or a relative measure that allows certain planning units with similar biodiversity features to be favoured over others. The cost of all planning units in a Marxan portfolio allows an assessment of the relative cost of conserving one planning unit versus another. We applied a relative non-monetary planning unit cost so that where choices existed between sub-catchments with similar biodiversity features, preference would be given to sub-catchments: (1) where ⩾10% of their area is already formally protected or (2) containing endemic fish species and at least 5 km of river in either an intact or moderately modified state. Each sub-catchment was assigned a uniform baseline planning unit cost (1000) and then all sub-catchments qualifying under criteria (1) or (2) were discounted to less than this baseline value (100). The discounted cost was determined through a series of trial and error runs in Marxan: the algorithm became more sensitive to favouring selection of qualifying sub-catchments using these relatively large discounts.

Using the above information, we ran Marxan 500 times with each run consisting of 5 million iterations. A map of the frequency that each sub-catchment was selected in each of the Marxan runs was thus produced (Ball and Possingham, 2000; Possingham et al., 2000) to use as an estimate of irreplaceability that would inform decisions regarding the focus areas.

3. Results

3.1. River condition

The extent of human modification on main river systems in South Africa has previously been documented (Nel et al., 2007), showing that less than a third of the main rivers can be considered intact (A or B categories), with the majority being moderately to

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largely modified (Table 1). Extending the Nel et al. (2007) analyses to include tributary condition supports their notion that tributaries are less impacted than main rivers (Supplementary Map 1), with 48% of the river length being in an intact state when tributaries and main rivers are considered, as opposed to just 30% when considering main rivers alone (Fig. 3).

3.2. Biodiversity pattern and process

The combination of 30 Level 1 ecoregions, two flow variability categories and four geomorphological zones produced 222 distinct river types across the country (Fig. 4). Over 5300 presence/absence records for freshwater fish endemic to South Africa were considered. These were concentrated along the permanently flowing rivers in the southern and eastern portions of the country (Supplementary Map 2).

Sixty-seven free-flowing rivers were identified, distributed mainly along the eastern coast of South Africa (Supplementary Map 3). The largest free-flowing river reach is the White Mfolzi (424 km), followed by the Mkomazi (300 km) and Doring (280 km). Only 15 (22%) of these are more than 100 km in length, with the majority (46%) between 50 and 100 km, and the remaining 32% comprising shorter, coastal rivers.

Almost 70% of the 259 estuaries in South Africa are considered a priority for some form of conservation action. Only 46 of these priority estuaries (18%) are linked to intact 1:500,000 rivers, many of which overlap with free-flowing rivers (Supplementary Map 3).

Protected areas, that with just minor expansion could incorporate whole river reaches, cluster mainly around the southern and western Cape (Supplementary Map 4), where there are numerous smaller protected areas in the vicinity of larger-sized Wilderness Areas or Mountain Catchment Areas. Other notable river systems are associated with larger-sized flagship protected areas, such as Kruger National Park and Greater St. Lucia Wetland Park (Supplementary Map 4).

3.3. Assessing current protection levels

Only 21% of the river types in the country are moderately to well protected in the current protected area system, and more than a third are not protected at all (Table 4). Disaggregating these results to geomorphological zones reveals that mountain streams have the highest proportion of moderately to well protected river types, while lowland rivers have the highest proportion of river types not protected. At an ecoregion level, gaps in protection levels for river types are particularly prevalent in the arid interior and eastern coastline of the country (Fig. 5). On the positive side, the current protected area system conserves at least one occurrence of each endemic freshwater fish species deemed to be likely to persist, and several of these species (31 of them) are captured more than once.

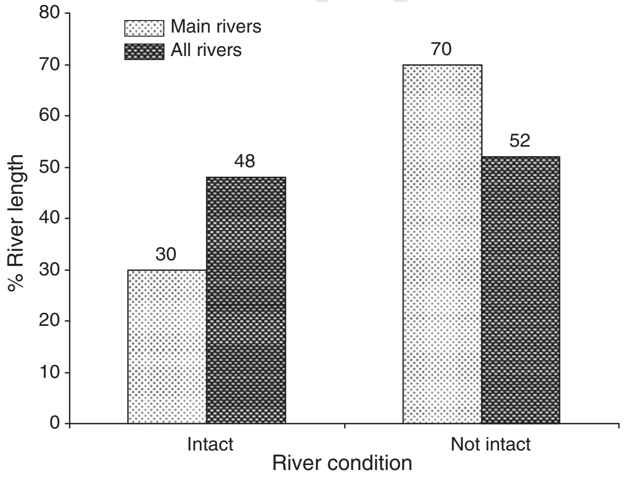

Fig. 3. Condition of main rivers compared to main rivers and tributaries.

3.4. Focus areas

The pattern of irreplaceability (Fig. 6) shows that options are limited for conserving representative examples of rivers associated with the Highveld, Drought corridor, South Eastern Uplands and Eastern Coastal Belt ecoregions (Fig. 4a). These are the ecoregions associated with high human populations and resource use pressures. Options still exist for locating protected areas in the under-protected semi-arid ecoregions of the Nama Karoo, and to a lesser extent, Southern Kalahari and Ghaap Plateau.

4. Discussion

Under the Convention on Biological Diversity, countries are committed to protecting 10% of representative terrestrial, marine and freshwater ecosystems (IUCN, 2003). This paper offers an approach to assessing progress toward achieving this target for freshwater ecosystems, a process that until now has been hampered by lack of methods (Revenga et al., 2005). This study also shows, for the first time, how a conservation planning algorithm can be applied in a freshwater setting to integrate a range of multiple conservation objectives (Table 3). The freshwater focus areas thus identified (Fig. 6) should be investigated further at a finer scale in terms of feasibility for incorporation into South Africa's protected area system.

Below we discuss generic recommendations to guide spatial planning for expansion of protected area systems across freshwater, terrestrial and marine realms. These recommendations are particularly pertinent to improving the way in which protected areas on land are located, designed and managed for both terrestrial and freshwater biodiversity.

4.1. Use an appropriate spatial scale and planning units

This national-scale study will ultimately inform local decision making around where best to locate individual protected areas. Planning units for rivers therefore needed to be small enough to ensure that focus areas direct protected area planning to specific places, while still considering the longitudinal and lateral linkages of freshwater systems. Commonly used terrestrial conservation planning units such as grid cells, hexagons or land ownership boundaries are inappropriate for freshwater conservation planning as they do not recognize these linkages. Although use of whole catchments as planning units would fully incorporate longitudinal and lateral linkages, their use in a study such as the present one would be limited since whole catchments are very seldom designated to protected areas. From several recent studies in freshwater conservation planning, it would seem that a pragmatic solution is to split whole catchments into sub-catchments of approximately 100–200 km^2 in size based on river segments (Linke et al., 2007). These sub-catchments only partially consider connectivity, and if chosen for protected area expansion will need to be augmented with other conservation mechanisms that manage external threats in connected systems to ensure that biodiversity within that protected area persists (Roux et al., 2008a).

4.2. Incorporate considerations of both biodiversity pattern and process

Most conservation planning efforts have focused only on representing biodiversity pattern, while fewer have specifically targeted

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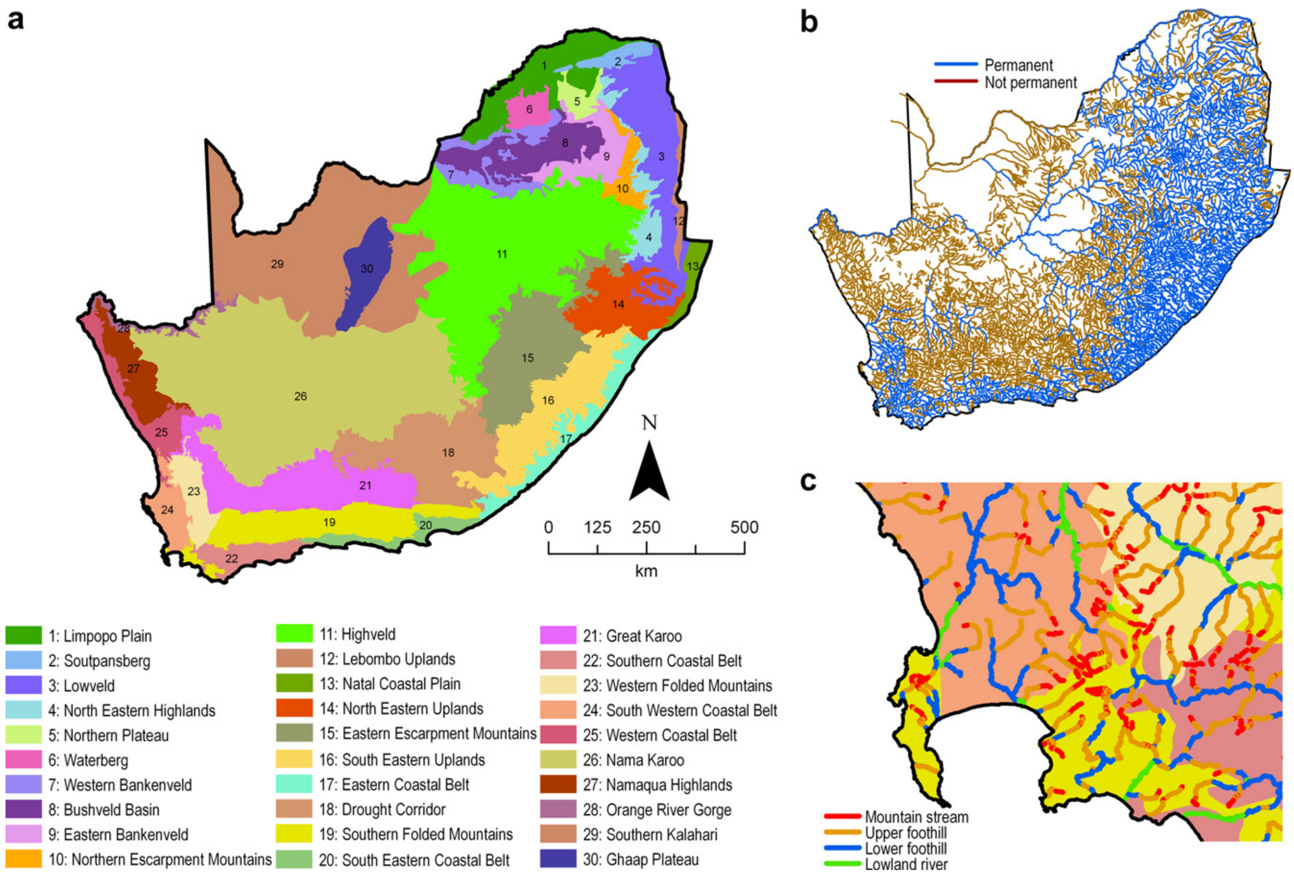

Fig. 4. GIS layers combined to derive river types: (a) Level 1 ecoregions; (b) flow variability are shown at the country-wide scale; while (c) geomorphological zones are depicted at a finer scale for ease of viewing. Data are described in Kleynhans et al. (2005), Department of Land Affairs (2005) and Rowntree and Wadeson (1999), respectively.

Table 4
Current protection levels for river types. Total number of river types within each protection level category are shown, as well as per geomorphological zone. Well-protected, moderately protected, poorly protected and hardly protected river types have at least 100%, 50%, 5% and >0% of their target conserved in protected areas.

Geomorphological zone	Not protected	Hardly protected	Poorly protected	Moderately protected	Well protected
Lowland river	30	4	6	3	6
Lower foothills	18	14	17	2	6
Upper foothills	16	13	24	3	4
Mountain streams	16	2	17	11	10
Total river types	80	33	64	19	26

important biodiversity processes (Pressey et al., 2007). This study incorporated aspects of both. From a technical GIS perspective, this was made possible by distinguishing between a river segment and river reach (Fig. 2) – the former was used for representation of biodiversity pattern; the latter to incorporate biodiversity processes.

The first objective of this study (Table 3) tackled representation of biodiversity pattern through setting targets for river types and endemic freshwater fish species. This objective also affords specific attention to threatened river types, defined by Nel et al. (2007) on the basis of the proportion of the total length of each river type still intact. By definition, sub-catchments containing threatened ecosystems will have limited options for conservation in intact systems; thus consideration of threatened ecosystems is incorporated in these analyses through considering focus areas with high irreplaceability values.

In addition to representation of biodiversity pattern, the conservation objectives (Table 3) dealt with representing examples of coarse-scale biodiversity processes associated with free-flowing rivers (objective 3) and catchment-estuarine linkages (objective 4). Such opportunities are rapidly disappearing owing to the widespread and escalating degradation of freshwater systems in South Africa (Nel et al., 2007) and worldwide (Nilsson et al., 2005; Dudgeon et al., 2006; Poff et al., 2007). These opportunities should therefore be high on the conservation agenda of all countries, and options for locating at least some of these river reaches within protected areas needs to be considered. Conserving these subcatchments will require exploring a range of conservation mechanisms, since such vast areas are seldom isolated from human populations.

The conservation objectives were also aimed at supporting the persistence of freshwater biodiversity within selected areas (Table 3). Objective 2 applies to the persistence of all focus areas, using river condition as a broad indicator of the likelihood that a river will support examples of biodiversity features likely to persist in the long term (*sensu* Groves, 2003). Objective 5 deals with longitudinal connectivity of selected focus areas only, identifying strategic opportunities for incorporating whole river reaches into existing protected areas and improving their likelihood of persistence. The clustering of these strategic opportunities in the southern and western Cape illustrates the positive role of large, strategi-

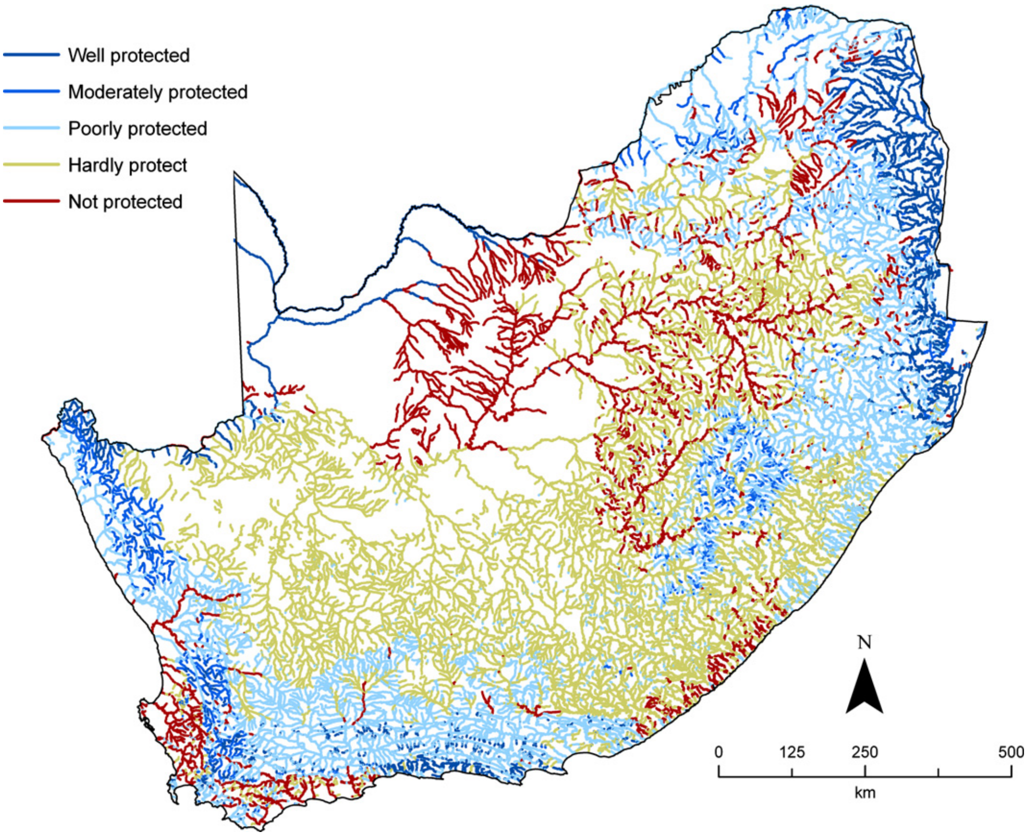

Fig. 5. Protection levels of each river type, where well protected, moderately protected, poorly protected and hardly protected river types have at least 100%, 50%, 5% and >0% of their target conserved in protected areas.

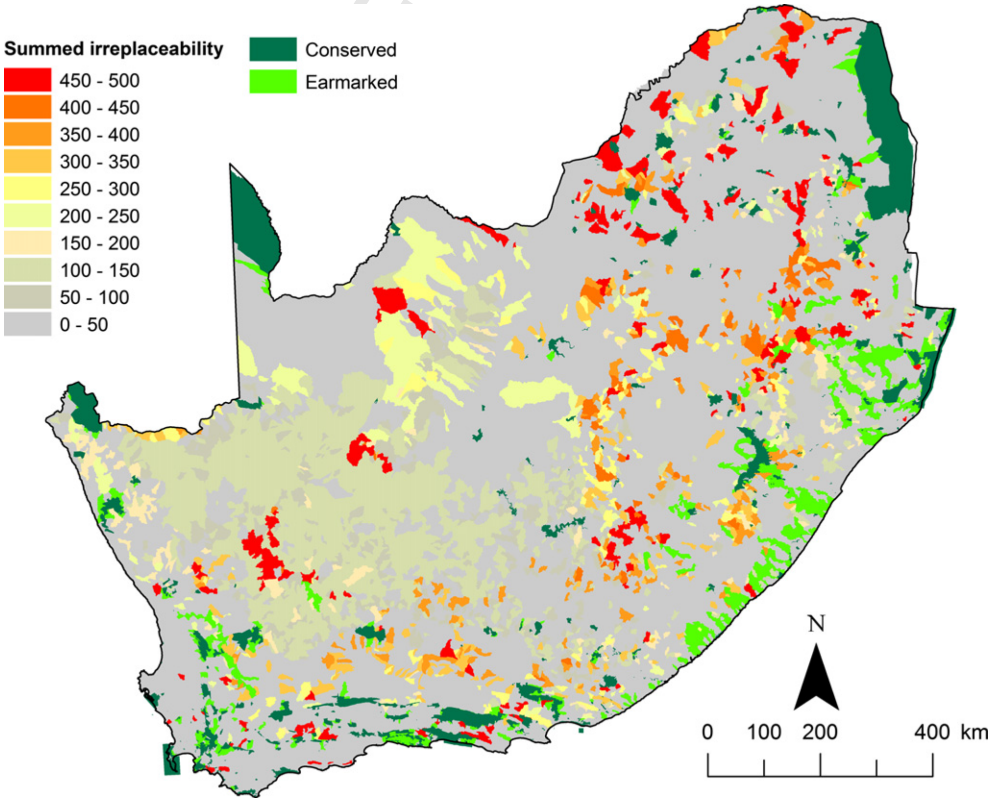

Fig. 6. Marxan frequency of selection (or irreplaceability) used for informing freshwater focus areas.

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cally-placed protected areas for river conservation. These areas can serve as focus areas that catalyze other formal and informal mechanisms of conservation in connected areas (Terborgh and Soulé, 1999).

4.3. Improve planning and management of individual protected areas

The focus areas give a national indication of where benefits for river biodiversity can best be realized. However, persistence of river biodiversity within individual protected areas needs to be further supported by the way in which they are both delineated and managed. Delineation of new protected areas can support the persistence of freshwater biodiversity by avoiding the use of rivers as boundaries of protected areas, and maximizing hydrological connectivity within the protected area. If possible, protected area boundaries should strive to incorporate the full range of geomorphological zones within each ecoregion and flow category (Fig. 4); if captured on the same river system, this will not only improve representation of river types, but will also incorporate river connectivity.

A first step towards enhancing management effectiveness of freshwater biodiversity within new and existing protected areas is to ensure that protected area management plans explicitly address freshwater conservation objectives that are monitored regularly. These objectives should include addressing freshwater conservation issues within the protected area (e.g. ensuring that tourist lodges and roads have minimal impact on river systems), as well as processes and threats external to the boundaries of the protected area (e.g. overexploitation of water resources).

4.4. Use irreplaceability and protection levels to inform focus areas

The pattern of irreplaceability used to guide freshwater focus areas (Fig. 6) provides a map of options available for achieving conservation targets. It is not a minimum set of sub-catchments required to achieve conservation targets (as would be provided by the best portfolio from Marxan). We chose not to use a single set solution to depict focus areas because these do not provide an indication of whether a selected sub-catchment is essential for achieving conservation targets or whether it can be replaced by other ones and is therefore negotiable. Understanding which areas are negotiable is important for integrating this assessment into an overarching protected area expansion strategy, which considers a multitude of objectives, such as consolidation of protected areas for ease of management, tourism access, and socio-economic constraints.

However, it is critical that this irreplaceability map is interpreted correctly within the context of protected area expansion. Selecting focus areas only from sub-catchments of high to moderate irreplaceability will undermine representation, since some low irreplaceability sub-catchments will still be needed to achieve conservation targets. This is particularly relevant for ecoregions where both irreplaceability and protection levels are low – locating at least one protected area in these ecoregions should be regarded as a conservation priority. In these instances, there will be a number of options from which to choose and location of the protected area should be further guided by other strategic objectives, such as terrestrial conservation priorities or socio-economic constraints.

4.5. Choose focus areas that incorporate a mixture of protection strategies

Fig. 6 shows focus areas that would achieve a range of different objectives. First, earmarked areas highlight opportunities for improving persistence of river systems already in protected areas, or for representing key biodiversity processes. Second, sub-catchments with a high irreplaceability value have very few substitute areas for meeting conservation targets. Protecting rivers in these sub-catchments will target river types or fish species that have very limited distributional ranges in South Africa, either naturally or because these are the last remaining examples in intact river systems. Third, as irreplaceability decreases, options for protected area placement increase. In these areas, protected area designation should be guided by other strategic objectives of the overarching protected area expansion strategy. Finally, areas of little benefit for protected area expansion (e.g. irreplaceability 0–50 in Fig. 6) should be avoided.

A common approach to prioritizing conservation action is to combine irreplaceability with vulnerability – a measure of the future risk of degradation (Margules and Pressey, 2000). The notion is that areas of high irreplaceability and high vulnerability should be secured before those associated with lower vulnerability. This framework is useful for planning that considers a range of conservation mechanisms; however, its use is limited in the context of protected area planning. Areas of high irreplaceability and high vulnerability are often areas where land-use conflict and land pur-

Table 5
Examples of focus areas for expanding protected area systems that would incorporate a mixture of protection strategies.

Strategy	Focus areas
Target under-protected and highly irreplaceable areas	• Sub-catchments with high irreplaceability in the Highveld ecoregion (Fig. 4a), which also faces ongoing degradation (Driver et al., 2005) • Sub-catchments with high irreplaceability in the South Eastern Uplands and Eastern Coastal Belt ecoregions (Fig. 4a), particularly those which overlap with areas identified as important for representing natural examples of coarse-scale catchment processes
Target under-protected areas, where several options exist for designation of large protected areas which combine terrestrial, freshwater and marine biodiversity	• Sub-catchments in the Nama Karoo ecoregion which have an irreplaceability score above 50 (Fig. 6), where opportunities exist to align with terrestrial and marine conservation, and other socio-economic constraints in the region. An initiative similar to those of the Greater Cederberg, Baviaanskloof and Gourtiz mega-reserves initiatives should be investigated
Incorporate natural coarse-scale catchment processes	• The relatively short coastal rivers of KwaZulu-Natal and the Wild Coast in Eastern Cape offer important opportunities for incorporating prime reference examples of systems where riverine and estuarine processes are still largely natural (Supplementary Map 3)

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chase costs are high – conserving ecosystems in such situations is often more pragmatically achieved through mechanisms other than formal protected areas. On the other hand, areas of low vulnerability that are currently under-protected often offer more cost-effective opportunities for the designation of large protected areas while still improving representation. We therefore recommend that protected area expansion strategies incorporate a combination of strategies in their schedule of action (Table 5), balancing protection strategies that focus on rescuing threatened biodiversity with strategies that prevent the biodiversity that is currently secure from becoming threatened.

4.6. Embed planning into an ongoing research and implementation process

This study is embedded in a real-world iterative process of protected area planning by South Africa's government department responsible for protected area planning and management (DEAT). To support the process of adaptive improvement, the scope of this spatial assessment needs to be extended, and several limitations will need to be addressed.

Freshwater ecosystems other than rivers need to be considered. This will require addressing data gaps for wetlands and groundwater at an appropriate scale for country-wide systematic conservation planning. It will also require identifying a sub-set of estuarine focus areas for protected area expansion, from the numerous priority estuaries already identified as requiring some form of conservation.

The species assessment needs to be expanded to include a wider array of freshwater taxa. In the long term, this limitation needs to be addressed through concerted inventorying of aquatic invertebrates at the species level. Inventorying could focus initially on key groups such as Trichoptera, Simuliidae, Plecoptera and Ephemeroptera since these groups represent the full spectrum of functional feeding groups (Heino and Soininen, 2007).

Almost 25% of the river types cannot achieve their targets in intact river systems. Restoration options for these river types should be strongly considered, but owing to the complexity of such analyses, were not considered here. This influences the final pattern of irreplaceability used to inform focus areas (Fig. 6). For example, the reason that the south-western portion of the country is depicted of limited value for protected area expansion is because there are no intact river systems remaining. In addition to considering restoration options, off-reserve conservation strategies should give attention to non-intact river systems that were largely over-looked in this study, since these systems may still retain important biodiversity refugia and functions that can make an important contribution to conservation through appropriate management (King and Brown, 2006).

The data used for main river condition (Kleynhans, 2000) need updating, and the level of confidence in the modelled tributary data is unknown. In addition, the land cover data used for modelling tributary condition is out of date and underestimates the extent of land degradation (Thompson et al., in press). Improving the quality of the river condition data would greatly support the credibility of the final product.

Free-flowing rivers identified in this study serve as an initial basis around which river scientists and practitioners need to further debate. Some of these rivers may not qualify as free-flowing owing to limitations of the input data: (1) farm dams built after 2005 have not been included in the connectivity analyses; (2) weir data were not included as there is no such national GIS layer and (3) water transfer schemes were not explicitly included in the analyses (however, for main rivers they were accommodated implicitly in the assessment of river condition). The buffering technique used may also disqualify some rivers which are indeed free-flowing since off-stream dams within 50 m of a river will be classified as instream dams.

We are only just beginning to tackle the issue of integrating freshwater and terrestrial focus areas for expanding protected area systems, and have not yet attempted to derive marine focus areas. These are key areas of research that need to be addressed in the next iteration. While it is intuitively appealing to run a single Marxan analysis for both terrestrial and freshwater biodiversity to derive a fully integrated pattern of irreplaceability, this can result in a loss of realm-specific information. For example, terrestrial planning units used to identify focus areas are orders of magnitude smaller than freshwater sub-catchments – 0.01 km^2 in size (S. Holness, unpublished data) compared to the average size of 170 km^2 for sub-catchments. Combining the assessment at the level of a sub-catchment would therefore result in a loss of terrestrial-specific detail. Consequently, alternative methods of integration also need to be explored, such as first selecting terrestrial planning units that overlap with freshwater focus areas and then expanding the focus areas to achieve residual conservation targets for terrestrial biodiversity features (Amis et al., in review).

5. Conclusions

The development of approaches to protected area planning for freshwaters is a timely topic given the ongoing degradation and massive threats faced by these ecosystems (Revenga et al., 2005; Dudgeon et al., 2006), and the subsequent surge of recent calls for urgent attention to be given to protecting freshwater biodiversity (Abell, 2002; Dunn, 2003; Fitzsimons and Robertson, 2005; Abell et al., 2007). This analysis has been specifically designed for guiding expansion of formal protected area systems. Realistically, protected areas can only play a partial role in overall efforts to conserve freshwater biodiversity, and will need to be supplemented with other less stringent conservation mechanisms. The recent hierarchical protection strategy put forward by Abell et al. (2007) proposes a multiple-use zoning framework for combining such mechanisms in which freshwater focal areas are embedded in critical management zones, which in turn are embedded in catchment management zones. The incorporation of the catchment management zone recognizes the ultimate need to embed freshwater focal areas and their associated critical management zones within integrated catchment management strategies.

This assessment suggests that large wilderness areas delineated according to sub-catchment boundaries have huge potential for representing natural examples of both freshwater biodiversity pattern and processes. Whatever their size, protected areas have the powerful ability to catalyze conservation activities in the surrounding catchments, providing the stimulus for the implementation of effective integrated catchment management. Protected area managers can learn from recent management practices in the Kruger National Park, South Africa (O'Keeffe and Rogers, 2003; Pollard et al., 2003), where explicit consideration of freshwater issues beyond the Park's boundary are now an intimate part of their adaptive management strategy, working towards inspiring surrounding communities and fostering a spirit of cooperation for conserving freshwater ecosystems both within and outside protected areas.

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of their fish data. Special thanks to Heidi van Deventer and Lindie Smith-Adao for GIS assistance, and to the broader protected area planning team, especially Stephen Holness and Mandy Driver for their advice and efforts to integrate freshwater concerns into protected area planning and management in South Africa.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2009.02.031.

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