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Scale-based freshwater conservation planning: towards protecting freshwater biodiversity in KwaZulu-Natal, South Africa

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SUMMARY

1. River systems have strong linear linkages. Innovative solutions to capture these linkages are required from aquatic conservation planners.
2. We apply an approach to freshwater conservation planning to freshwater ecosystems of KwaZulu-Natal (South Africa), using generic conservation planning software. We used a two-step, hierarchical process to capture catchment- and local-scale dynamics, where priority primary catchments were first identified and then used at a second level for selecting priority subcatchments, which served as planning units at a finer scale.
3. We set quantitative targets for defined freshwater biodiversity features. Priority planning units at both catchment levels were selected using modified weighted cost discounts and penalties, which included the presence of priority estuaries and free-flowing rivers, planning units falling within priority primary catchments, planning units identified as important in an existing terrestrial conservation plan and the degree of catchment degradation. Ecological processes were incorporated by discounting planning units important for surface and groundwater yield.
4. Upstream–downstream connectivity was achieved by linking adjoining subcatchments associated with main rivers and wetlands and enhanced by setting high targets for subcatchments through which eels (*Anguilla mossambica*) must migrate.
5. The hierarchical approach of selecting priority primary catchments and using these to affect subcatchment costs, plus the use of high targets for migratory fish species, is applicable to any freshwater conservation plan to favour planning unit selection within selected basins, while facilitating connectivity in upstream–downstream subcatchments.

Keywords: connectivity, MARXAN, nested hierarchy planning units, systematic conservation planning

Introduction

Strong linear linkages exist in river systems. Physical processes act predominantly in an upstream to downstream direction, while biological processes typically act in both directions. The network of drainage channels defines the degree of connectivity between hydrological 'landscapes', where subcatchments within the same primary catchments are better connected than subcatchments falling in adjacent primary catchments. Finding suitable ways of incorporating upstream–downstream connectivity (Linke *et al.*, this issue) is a central challenge to freshwater 2 conservation planning.

The challenge of planning for connectivity is further compounded by the close relationship between freshwater systems and catchment conditions. This poses particular conceptual problems in identifying priority

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areas for conservation action and conserving aquatic systems (O'Keeffe, Danilewitz & Bradshaw, 1987). The intimacy between catchment condition and river health is one reason why freshwater systems are amongst the most threatened systems globally, having experienced the most rapid and greatest amount of species losses to date (World Conservation Union, 2000; Abell, 2002; Groves, 2003; Jenkins, 2003).

The situation is particularly dire in southern Africa (Driver *et al.*, 2005; Nel *et al.*, 2007), exacerbated by this region being ranked as a high water stress zone, because of intense competition between water users (Alcamo *et al.*, 2003). The relative water scarcity within South Africa and difficulties in meeting the requirements in the national Water Act for the ecological reserve (i.e. the quantity and quality of water required to protect the aquatic ecosystems of the resource; Republic of South Africa, 1998) are aggravated by pressures to supply water to burgeoning economic growth (CNCI, 2006; Eskom, 2007). This is alarming given that flow regulation and change in land use are the primary threats to river health in South Africa (Davies, O'Keeffe & Snaddon, 1993). A large body of scientific literature recognises the links between catchment condition and river function (e.g. Millennium Ecosystem Assessment, 2005a,b), as well as the negative ecological impacts of interbasin transfer schemes (e.g. O'Keeffe & de Moor, 1988; Snaddon & Davies, 1998; Rivers-Moore *et al.*, 2007a), which are increasingly seen as a means to alleviate water stress in the drier regions of South Africa (DWAF, 2002).

Such complexities in aquatic systems are typically not addressed in terrestrial conservation planning, resulting in freshwater conservation planning lagging behind terrestrial conservation planning by at least a decade (Groves, 2003; Linke *et al.*, this issue). Protection of river fragments alone will not achieve conservation goals. Innovative solutions that recognise this 'nested hierarchy' in the aquatic environment – i.e. placing aquatic systems in a catchment context, from subcatchment to primary catchment, in a connected way – are required to achieve defendable planning for aquatic systems. This involves a return to those fundamental principles that facilitate the understanding of freshwater systems and the development of spatial planning from this departure point. One such principle is that biological systems, particularly freshwater systems, are inherently hierarchical in nature (Frissel *et al.*, 1986; Margules & Pressey, 2000). In the absence of comprehensive biological spatial data across a range of taxa, using biodiversity surrogates that spatially represent such hierarchies is one solution. Environmental variables in the catchment explain the variation in, *inter alia*, invertebrate distribution (Richards, Johnson & Horst, 1996). Higher-level surrogates are less precise, but more efficient at integrating ecological process (Margules & Pressey, 2000). Hierarchical classifications present both a tool to capture biodiversity patterns and processes, and a set of hypotheses to test actual biodiversity patterns against as data improve. The precedent of developing and using such hierarchies as spatial analysis tools in freshwater conservation planning is well established (Groves, 2003; Higgins *et al.*, 2005; Rivers-Moore & Goodman, in press).

Systematic conservation plans are broadly governed by two principles: *representation* and *persistence* of biodiversity (see Margules & Pressey, 2000). Incorporating the principle of representation into a freshwater conservation plan requires conserving an adequate sample of the variety of freshwater biodiversity features within the planning region. This requires mapping these features across the entire landscape (e.g. river types of KwaZulu-Natal, developed by Rivers-Moore & Goodman, in press), as well as quantifying the minimum requirements for each feature (also referred to as *conservation targets*). Incorporating the principle of persistence into a conservation plan requires the maintenance of all natural processes that support and generate freshwater biodiversity. Setting quantitative conservation targets enables an assessment of the conservation value of an area in designing efficient and effective conservation area networks.

It is within this context that the need for a freshwater conservation plan for KwaZulu-Natal was identified (Rivers-Moore, Goodman & Nkosi, 2007b), to complement [3] an existing terrestrial conservation plan that identified priority terrestrial areas (Goodman, 2007, unpubl. data). Limited protection to freshwater systems [4] in the province is provided through a network of formally protected areas and augmented with privately owned land parcels incorporated into a stewardship programme. While it is not possible to allocate too high a level of protection to all water resources throughout the country without prejudicing social and economic development, it is equally not sustainable for all resources to be classified at a uniformly low level of protection so as to permit maximum use from competing land users. A strong legislative framework that supports South Africa's obligations to international conservation agreements is available to protect freshwater resources (Driver *et al*., 2005; Roux *et al*., 2006). According to these agreements and legislation, each province in South Africa is required to produce bioregional plans (Driver *et al*., 2005), based, amongst others, on systematic conservation planning principles.

This article has two aims – to present the freshwater conservation plan developed for KwaZulu-Natal, South Africa as a generic framework for other planning regions and to highlight future research priorities to refine this plan.

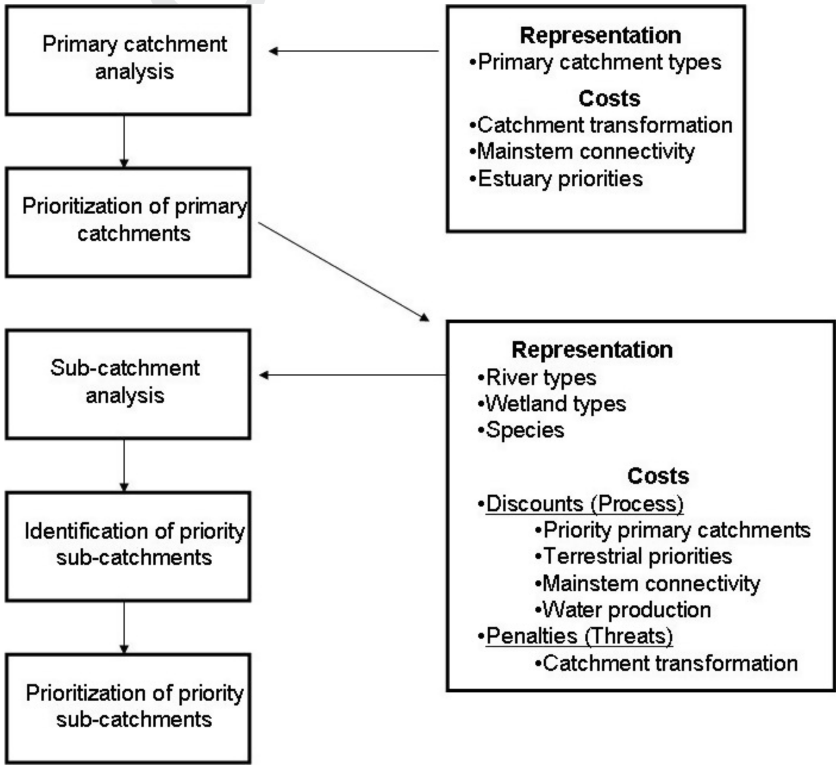
Methods and results

Study area

The entire province of KwaZulu-Natal, one of nine provinces in South Africa in the east of the country, was used as the planning region in this study. Freshwater conservation planning in this region is relatively simple, because the hydrological and administrative boundaries largely correspond, with most of KwaZulu-Natal's rivers arising either in the western escarpment zone, or internally within the province, and draining east into the Indian Ocean. Water availability generally follows an altitudinal gradient, with most of the rainfall falling in the higher western escarpment areas. KwaZulu-Natal is also the only province in South Africa that can truly be described as not being water scarce under current climatic conditions and water use demands, in spite of certain catchments being over-allocated (withdrawals-to-availability ratios – Alcamo *et al*., 2003). Particular threats to freshwater biodiversity within KwaZulu-Natal include, *inter alia*, interbasin transfer schemes; changes in river sediment budgets because of land cover change, catchment degradation and mainstem impoundment; and loss of river connectivity through impoundment and abstraction.

Conservation planning approach

The steps in developing the aquatic conservation plan for KwaZulu-Natal followed the basic six-step process described by Margules & Pressey (2000). In this article, the first five steps (Fig. 1) are outlined later,



12 **Fig. 1** Flowchart of steps, and associated inputs and outputs, in the conservation planning process. Primary catchments make up the planning units at the first level of analysis, while subcatchments form the planning units at the second level of analysis.

while the sixth step (management actions and monitoring) remains to be implemented. Methods and results have been combined for clarity.

The conservation planning process, in its broadest form, begins with a planning unit-by-features matrix, where each feature has an associated conservation target. The planning region is divided into planning units, the extent of all biodiversity features within each planning unit is assessed, and the contribution that each unit makes to the conservation targets can be calculated. Within the conservation planning process, planning units are selected using a selection algorithm, where the number of times a planning unit is selected during the iterations provides an indication of its importance in meeting the defined targets; i.e. a measure of its *irreplaceability*. In a resource-limited reality, conservation planning algorithms aim to achieve the greatest representation of conservation features at least cost (i.e. a minimum set reserve system – Possingham, Ball & Andelman, 2000). Using this concept of irreplaceability, combined with other assessments of costs, generic conservation planning tools can help to select the configuration of planning units that is most efficient at achieving overall conservation targets.

Step 1: measure and map biodiversity

Feature type classifications To quantify surrogate features for aquatic biodiversity (the catchment, wetland and river types), this step in the conservation planning process aimed at developing appropriate classifications for feature types. In the absence of extensive spatial aquatic biodiversity data for the province, abiotic spatial surrogates were used to represent biodiversity pattern (see Rivers-Moore & Goodman, in press, for further details). Abiotic surrogates were used for biodiversity at two different scales, primary and subcatchment.

River types were defined using a three-level hierarchical classification, viz. aquatic biogeographic regions (encompassing one or more major river basins); physiographic regions (river profile types) and flow type regions (reflecting flow variability) (see Rivers-Moore & Goodman, in press). This classification combined both top–down (the use of spatial abiotic surrogates to represent biodiversity patterns) and bottom–up (biological data were used to verify the physiographic regions) approaches to define spatial patterns. The classification was based on the conceptual hierarchical approach of Frissel *et al.* (1986) and is has some similarities with that of, for example, Higgins *et al.* (2005).

Primary catchments were defined as major hydrological basins, where each primary catchment constituted the drainage basin for a mainstem river draining into an estuary. At the landscape level, two assumptions were made regarding primary catchment types and aquatic biodiversity: first, physiographic regions correspond with longitudinal river zones and have different aquatic communities; and secondly, the number and area of different physiographic regions within each primary catchment (see Rivers-Moore & Goodman, in press) could be used as surrogates for differences in gamma diversity among primary catchments, i.e. the conservation of representative gamma diversity could be achieved by identifying different primary catchment types. The area of each physiographic region in each primary catchment (an indication of maximum potential river profile heterogeneity) was calculated and converted to a percentage. Catchment types (based on the number and percentage contribution of physiographic regions within each primary catchment, representing river profile heterogeneity) were defined using a cluster analysis (Euclidean distance measure; un-weighted pair-group averages) (McCune & Mefford, 1999). Having recognised that the biogeographic regions within the province represent distinct aquatic communities based on their different geological histories, we further refined the initial catchment types (which did not consider biogeographic regions in the cluster analysis as this resulted in too many groups) by intersecting these with the aquatic biogeographic regions. This step added further resolution to the classification by recognising that similar catchment types could be found in different biogeographic regions and therefore have functionally similar aquatic communities made up of different species.

Eight primary catchment types were discernable at the fifth level of a cluster analysis, based on the topographic heterogeneity within each primary catchment. We chose the fifth level of clustering as higher levels (third to fourth) resulted in too coarse a classification, and lower levels (sixth) gave too many primary catchment groups. Broadly, primary catchment types either fell into a coastal zone, a coastal and midland zone, or a coastal–midland escarpment zone (Fig. 2).

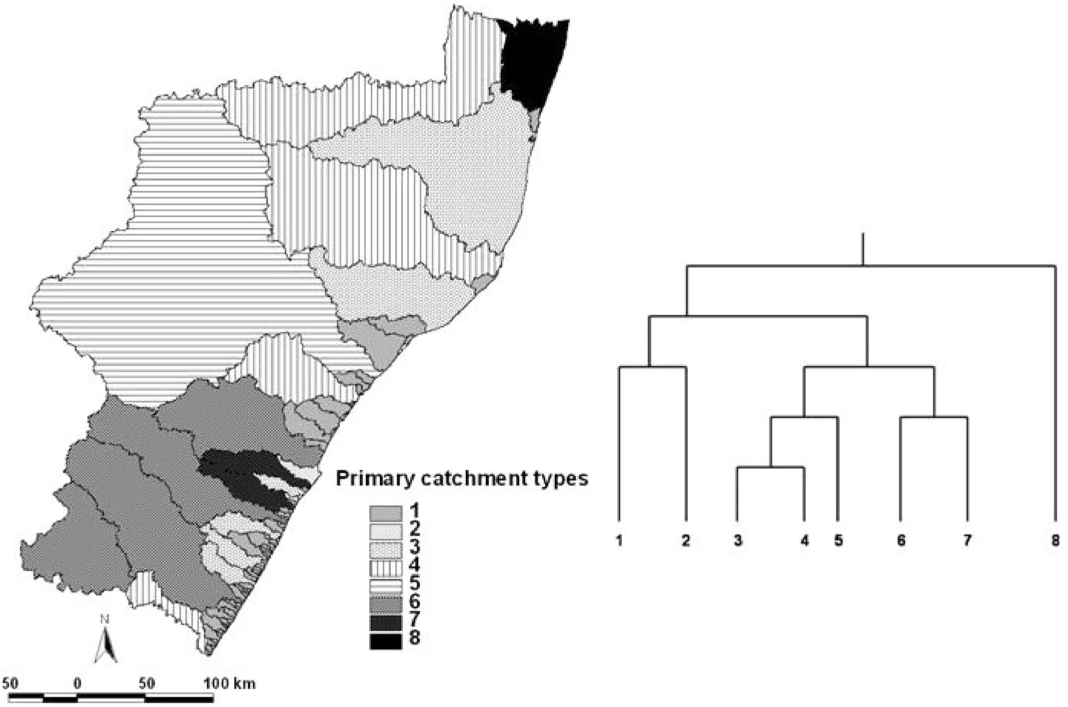


Fig. 2 Classification of primary catchments in KwaZulu-Natal into eight types (left), and dendrogram showing relatedness of primary catchment types (right). 13

For subcatchments, river types were based on aquatic biogeographic region, river profile heterogeneity (physiographic region) and flow type, according to Rivers-Moore & Goodman (in press). This classification was based on the hierarchical approach of Frissel *et al.* (1986), where river systems are hierarchically arranged from microhabitat to river basin. Because of the risks of oversimplification and under-representation in setting river type length targets at a small scale only (Rivers-Moore *et al.*, 2007b), river coverages at two scales were classified according to river type and incorporated into the conservation plan. Perennial and non-perennial mainstem rivers (i.e. the stem of the highest order river per primary catchment, from the sea to its origin at the highest altitude in the catchment) were selected using the 1 : 500 000 rivers coverage developed by South Africa's Department of Water Affairs and Forestry (DWAF, 2005) and supplemented from the 1 : 50 000 rivers coverage to ensure that each primary catchment had at least one mainstem river. To explicitly include tributaries that are typically less continuous in the landscape along a primary catchment's longitudinal axis, but act as refugia for the more heavily used mainstem rivers, perennial rivers were selected from the 1 : 50 000 coverage.

In total, 235 feature types were included in the KwaZulu-Natal freshwater conservation plan, made up of perennial and non-perennial mainstem rivers, 1 : 50 000 perennial tributaries, wetlands, species of conservation concern and special features. A total of 46 800 km of rivers were identified for input into the conservation plan. Of a potential 74 river types for each of mainstem perennial, non-perennial and low-order perennial streams, 69, 32 and 63 actual river types were assigned, respectively. River lengths within the province for each of the three broad river type groups were 16 800, 1800 and 28 200 km, respectively. Similarly, 49 wetland types were defined for the province, with a total area of 585 000 ha. Three hot springs were identified within the province, as unique features that potentially represent thermal ecotones in freshwater systems.

Wetland types were based on a gradient analysis of vegetation samples from lentic wetlands, to derive a floristic classification. Kotze & O'Connor (2000) identified distinct changes in the dominant plant species within permanent wetlands at different altitudes. We adopted their groupings of montane, highland, midland and lowland wetlands, along with their altitudinal cut-offs. A limitation of this study was that it did not sample and therefore distinguish wetlands below 500 m a.s.l. Based on expert knowledge, this group of coastal lowland wetlands was subdivided based on geomorphic setting, vegetation physiognomy and dominant plant species. Geomorphic setting distinguished between riparian and non-riparian wetlands, while physiognomy distinguished between forest, woodland, and tall- and short-grass and sedge wetlands. This classification was refined further by assigning wetlands to the relevant biogeographic regions.

Planning units Planning units were defined at two scales (see Fig. 1), to select areas to achieve conservation targets: primary catchments and subcatchments, nested within these. The use of both scales together with the planning process allows for hierarchical planning. In this nested framework, gamma diversity was represented at the landscape level by defining primary catchments; alpha diversity was addressed using subcatchment planning units, which, when linked together with an efficient upstream–downstream pattern, aims to capture beta diversity patterns.

In total, there were 125 planning units for the first level (primary catchments), and 4602 planning units at the second level (sub-catchments). The subcatchments nested within these primary catchments were derived using the WATERSHED function in IDRISI, and based on a 90 m digital elevation model (USGS, 2005) and ranged in size from 18 to 44 000 ha, with a mean area of 2078 ± 1462 ha.

Planning unit features At the next phase of the conservation planning process, we linked biodiversity features to their corresponding planning unit in a database file (see Fig. 1). Vector coverages were intersected with the planning unit coverage to enable calculation of the amount (area or length) of each feature per planning unit. A resource matrix for the planning units was then attributed to the features listed in Table 1. For the first-level planning units (primary catchments), the feature for each unit was its primary catchment type and assumed to represent major gamma diversity gradients within the province (Table 1).

Four categories of biodiversity features were selected to identify beta and alpha freshwater biodiversity patterns at the subcatchment scale across the province: river and wetland types, species of conservation significance and special features (hot springs – as possible thermal ecotones; see Viers & Israel, this issue) (Table 1). Data on endemic or critically endangered species were extracted from Ezemvelo KZN Wildlife's (EKZNW) biodiversity database. Species records of all spatial and temporal resolution (GPS point to quarter-degree precision) were used, since the spatial resolution of the planning units was on average 20 km^2, which compensated for spatial inaccuracies in the data.

Twenty-two species with aquatic associations were selected for the conservation plan. These included five species of macroinvertebrates, two species of reptiles, three species of amphibians, four species of fish, one species of bird (wattled crane – *Bugeranus carunculatus*) and seven species of wetland plants. In the case of the wattled cranes, records based on nest sites rather than sightings were used. Nesting sites of this species, which occur in lentic wetlands, are critical habitat for population viability and therefore appropriate for spatial planning. In total, 1694 species records were used, of which 90 were active/historic wattled crane nest sites, and 156 were locations where eels had been recorded. Within KwaZulu-Natal, eels have been recorded in 29 of the 125 primary catchments and would have passed through approximately 700 of the 4602 subcatchment planning units to arrive at the uppermost sites in the corresponding river systems.

Step 2: identify targets and goals

The conservation goal (*sensu* Margules & Pressey, 2000) was to identify representative basins and subcatchments to conserve aquatic biodiversity features. At the primary catchment level, targets were set, so that at least one of each catchment type was selected, to define priority primary catchments within KwaZulu-Natal. Targets for primary catchment types ranged from 20 to 100%, depending on the number of primary catchments per catchment type. A further target of 50% of all primary catchments where migratory eels had previously been sampled was set, as a process target.

At the subcatchment level, quantitative targets were set for defined freshwater biodiversity features, where

Table 1 List of freshwater features used in the plan to achieve gamma, beta and alpha biodiversity representation at two spatial scales in KwaZulu-Natal, a brief explanation, and targets

Representative features	Explanation	Target (%)
Planning units	Nested hierarchy of subcatchments within primary catchments	NA
Primary catchment analysis		
Primary catchment types	Classification based on profile heterogeneity and biogeographic regions. Aim to capture gamma diversity	20–100
Mainstem connectivity	_Anguilla mossambica_ (Plain long-fin eel)	50
Subcatchment analysis		
Main rivers (perennial)	69 river types, total length 16 800 km	20
Main rivers (non-perennial)	32 river types, total length 1800 km	20
Tributaries (perennial)	63 river types, total length 28 200 km	15
Wetlands	49 wetland types, 585 000 ha	20
_Aciagrion pinheyi_*	Emerald striped slim (Odonata)	20
_Afrixalus spinifrons intermedius_*	Intermediate Natal leaf-folding frog	20
_Agriocnemis ruberrima ruberrima_*	Orange whisp	20
_Barbus gurneyi_*	Redtail barb	20
_Barleria greenii_*,†	Wild bush petunia	20
_Brachystelma ngomense_*,†	Brachystelma	20
_Bradypodion melanocephalum_*	Black-headed dwarf chameleon	20
_Catha abbottii_*,†	Pondo khat	20
_Chlorolestes draconicus_*	Drakensberg sylph	20
_Dahlgrenodendron natalense_*,†	Natal quince	20
_Geranium ornithopodioides_*,†	Geranium	20
_Gladiolus cruentus_*,†	Kloof suicide lily	20
_Hyperolius pickersgilli_*	Pickersgill's reed frog	20
_Kniphofia latifolia_*,†	Broad-leafed poker	20
_Labeo rubromaculatus_*	Tugela labeo	20
_Labeobarbus natalensis_*	KwaZulu-Natal yellowfish	20
_Leptopelis xenodactylus_*	Long-toed tree frog	20
_Montaspis gilvomaculata_*	Cream-spotted mountain snake	20
_Pseudagrion umsingaziense_*	Umsingazi sprite	20
_Silhouettea sibayi_*	Sibayi gobi	20
_Urothemis luciana_*	St Lucia basker	20
Bugeranus carunculatus‡	Wattled crane nests – active and historic	20
Hotsprings	Potential thermal ecotones with unique biota	100
Process features (costs)		
Mainstem connectivity	_A. mossambica_ (Plain long-fin eel)	80
Priority primary catchments	Facilitates grouping of sub-catchments within identified primary catchments	NA
Terrestrial priorities	Achieves partial integration with existing terrestrial conservation plan	NA
Water production	Zones necessary for maintaining river baseflow	NA

*Provincial endemic.

†Endangered.

‡Critically endangered.

mainstem river targets were based on a percentage of the total length of each river type, wetland targets were based on a percentage of the total area of different wetland types, and species targets were set according to a percentage of the total number of planning units containing each species. In the absence of objective methods, typically a target value of 20% was chosen (Roux *et al.*, 2006). For perennial tributaries, a 15% target length of each river type was used, so that tributaries would be represented, but for a deliberately chosen lower target, since we assumed that many tributary types would already be represented by the 20% target for mainstem river types. We used a 100% target for special features (only hot springs at this stage) because of their rarity in the landscape. Higher targets were set for critically endangered species (100%) based on the desire to see no further reduction in the status of these species,

Table 2 Summary statistics of scenarios and costs associated with the KwaZulu-Natal Freshwater conservation plan (subcatchment planning unit level) [11]

		Mean	Minimum	Maximum	Final
No. scenarios	23				23
No. runs/scenario	200		100	200	200
No. iterations/scenario	1 000 000				1 000 000
Variables (included/excluded)	Costs, protected areas, boundary lengths, BLMs, tributaries				
Total targets	235	235	235	235	235
Area (% KwaZulu-Natal)		26.3	16.6	49.5	38.2
Cost (ha)		1 676 134	16 658	3 531 691	16 658
Boundary lengths		155 510	0	920 000	68 500
Boundary length modifiers (BLMs)	0, 0.1, 0.5, 1, 10				0.1

and for migratory species (80%) to achieve better mainstem connectivity.

Step 3: review existing conservation areas

Protected areas were considered in the conservation plan, even though their role in directly contributing to conservation targets was unknown. Any subcatchment that had more than 90% of its area under formal protected areas was assigned a protected area status. The number of targets that the protected areas could achieve currently was assessed. Within the existing protected area network, only 35 of the 235 features achieve their targets.

Step 4: select additional areas

Selecting freshwater conservation areas In the fourth step of the conservation planning process, planning units and biodiversity features were selected using conservation planning software. The conservation planning software MARXAN v.1.8 (Ball & Possingham, 2000; Possingham *et al*., 2000) was chosen as most suitable to assist in selection of additional areas. This software is designed to provide a near-optimal reserve configuration based on targets set for conservation features. Its objective is to meet as many targets as possible based on least cost per planning unit, using a simulated annealing optimisation method (see Ball & Possingham, 2000). Data were first converted into the appropriate format for MARXAN using the [6] Arcview 3.2 (ESRI 1999) extension CLUZ (Smith, 2004).

Planning unit costs Costs were calculated at two levels, for primary catchments as planning units, and for subcatchments as planning units. In each case, in the absence of provincial data on monetary values, area was used as a cost surrogate, since we assumed that smaller planning units that met feature targets would be cheaper to acquire and manage than larger planning units which achieved the same targets.

A large emphasis in the conservation plan was placed on deriving weightings for the costs and penalties. Planning units with desirable ecological processes were preferentially weighted, while subcatchments that are highly transformed were negatively weighted. Ecological processes necessary for achieving biodiversity persistence were incorporated at this stage rather than as features for two reasons, viz. that processes are easier to represent as continuous variables rather than as discrete entities, and because processes drive biodiversity patterns and are therefore distinct from features. Where there are multiple options for meeting targets for biodiversity features, the cost weightings became important in preferentially selecting planning units with important ecological processes or those in good condition.

Discounts and penalties were ranked by aquatic specialists at a workshop. These were hierarchically weighted using multicriteria evaluation software (Zhu & Liu, 2005) based on pair-wise comparisons in a continuous rating scale in the Analytic Hierarchy Process (Saaty, 1980). This approach was used to weight the factors with a level of objectivity and repeatability and to provide consistent weightings where factors are multiple. A consistency value of 0.1 was used as the selection threshold, as recommended by Saaty (1977).

At the first level of the weightings, cost discount factors (CDF) were weighted based on raster images representing ecological processes considered to be important in conservation planning. The CDF for the primary catchments was calculated from the following attributes (weighting scores in brackets):

- Free-flowing rivers associated with primary catchments (0.875), which were defined as 'any river that flows undisturbed from its source to its mouth, either at the coast, an inland sea or at the confluence with a larger river, without encountering any dams, canalisation, weirs or barrages and without being hemmed in by dykes or levees' [7] (WWF, 2006, p. 2);
- Primary catchments linked to priority estuaries (0.125), as identified by EKZNW (2006, unpubl. data) in terms of their role in biodiversity conservation. Thus, estuaries act as one of the drivers for selecting primary catchments in the freshwater conservation plan, by discounting priority planning units.

The CDF for the subcatchments was calculated from the following attributes (consistency value = 0.032; weighting scores in brackets):

- Subcatchments within previously identified priority primary catchments (0.137);
- Subcatchments through which free-flowing rivers pass (0.533);
- Subcatchments containing priority estuaries (0.052), as identified by EKZNW (2006, unpubl. data) in an estuarine conservation plan;
- High surface water yield/runoff areas (0.184) (Rivers-Moore *et al*., 2007b);
- High groundwater areas (0.094) (DWAF, 2007).

In both instances, a raster cost discount image was derived by adding each weighted cost discount raster layer together. Because of the way in which weightings were calculated, a combination of cost discount images could thus yield a maximum CDF of one for the primary catchment and subcatchment discount surfaces.

For the subcatchments, we incorporated a subsequent step to promote integration with a previously developed terrestrial conservation plan through the use of a terrestrial discount (TDF). This was calculated as the per cent of each planning unit previously identified as being of conservation importance in the terrestrial conservation plan. These values were also rescaled to range from zero to one. The purpose of this weight was to select planning units common to both the freshwater and terrestrial conservation plans in preference to those which were not, where alternatives existed in meeting biodiversity targets.

The penalty factor (CPF) was calculated as the percentage transformation within each planning unit, and rescaled from zero to one. Ideally, ecosystems in good condition should be selected for conservation purposes, since these are the ecosystems that represent the biodiversity of the region and may persist in the long term. Catchment condition at both the primary catchment and subcatchment scales was determined based on the degree of landscape transformation as reflected in the 1995 and 2000 land cover layers for South Africa. Land cover classes considered to be transformed include urban, cropland, plantation and degraded. Untransformed land cover comprised of those classes containing natural vegetation cover.

The cost factors were multiplied by the weightings for each cost modifier (D = discount, P = penalty and T = terrestrial), to yield final cost modifiers, according to eqns 1–3. Pair-wise weightings for discount and penalty at the primary catchment level were 0.2 and 0.8, respectively. Pair-wise weightings for discounting (D), terrestrial units of importance (T) and penalty (P) at the subcatchment level were 0.132, 0.174 and 0.694, respectively (consistency value = 0.069). These weightings reflect the relative importance of the three factors in achieving the final modifier and were again derived using the pair-wise comparisons in a continuous rating scale in the Analytic Hierarchy Process (Saaty, 1980), and using a consistency value of 0.1 was used as the selection threshold (Saaty, 1977).

$$D = \mathrm{CDF} * W_1 \tag{1}$$

$$P = \mathrm{CPF} * W_2 \tag{2}$$

$$T = \mathrm{TDF} * W_3 \tag{3}$$

where W_i = weightings for different cost multiplier components.

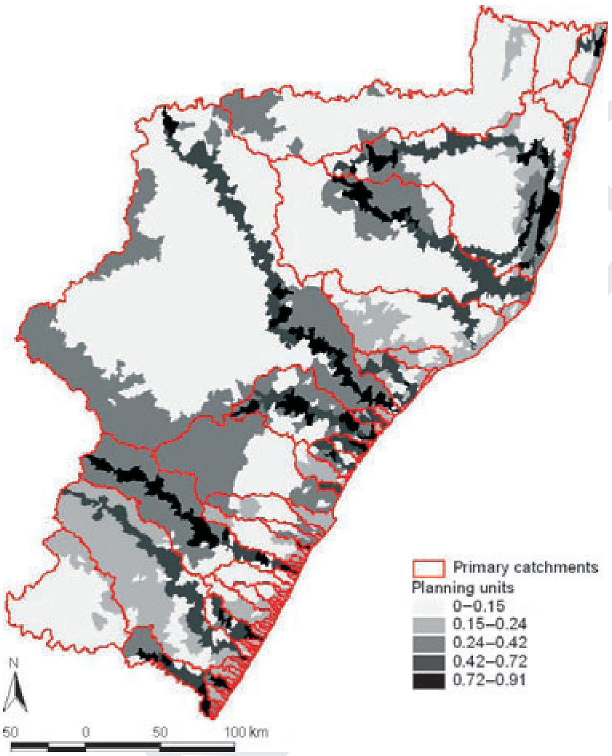
The final cost for each subcatchment was achieved by raising the initial cost (area in ha) of each subcatchment by a modifier (eqns 4 & 5).

$$\mathrm{Cost}^M \tag{4}$$

$$M = P - (D + T) \tag{5}$$

Recognising that values assigned to costs are arbitrary, a sensitivity analysis was undertaken to understand the sensitivity of the conservation plan solution to the addition of successive cost discount surfaces. This was achieved by comparing area: portfolio cost ratios for different cost scenarios.

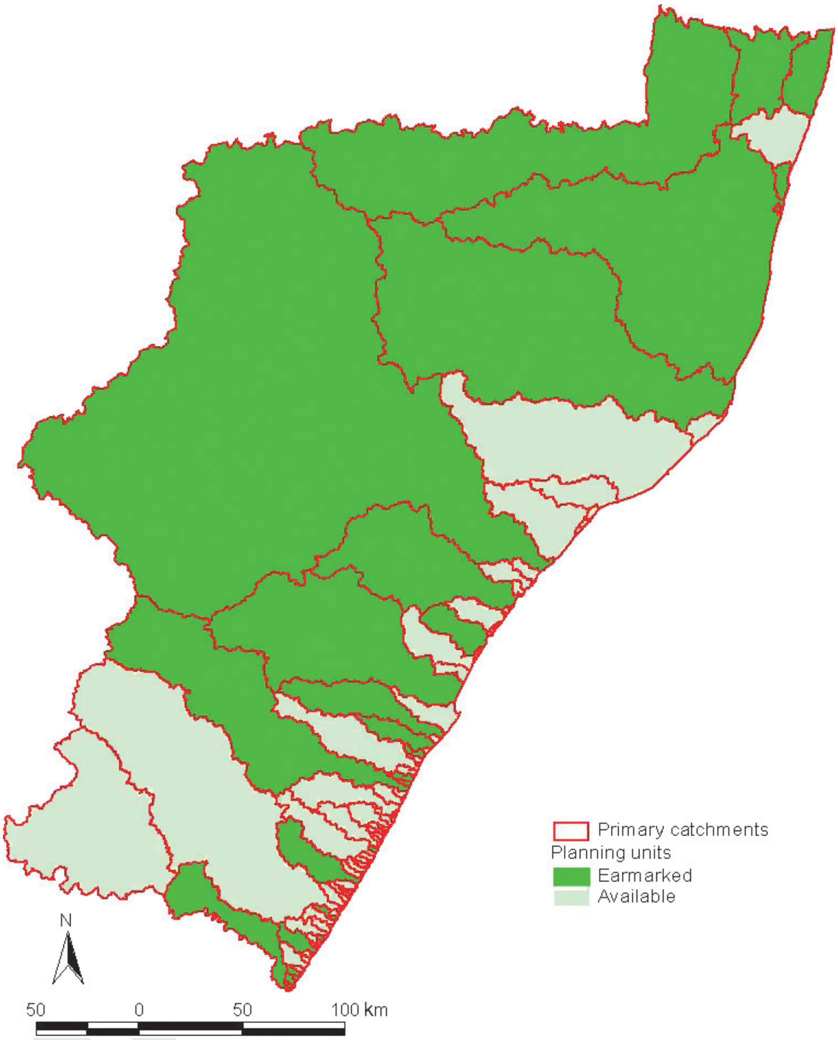
The cost discount surface was used to preferentially weight the subcatchment planning units according to Fig. 3. Successive CDFs changed the area: cost ratio in a linear fashion. This included 27 primary catchments selected from a possible total of 125 primary catchments from the MARXAN iterations (Fig. 4). The use of a power function to modify the basic area cost, in combination with the weightings chosen, influenced the costs exponentially, so that highly degraded planning units had exponentially greater costs than less degraded planning units. Such a cost algorithm provided greater sensitivity than a linear cost modifier. Two hundred and seventy-two subcatchments were identified as priority areas in the previously developed terrestrial conservation plan, which influenced selection of planning units common to both terrestrial and freshwater conservation plans.



14 **Fig. 3** Grid surface combined cost discount factor values showing weighting amount by which costs (area) were discounted for the KwaZulu-Natal freshwater conservation plan., where grey shading represents weightings of ecological processes up to a maximum of 1, with black being the most highly discounted (i.e. most favoured) planning units.

Scenarios Multiple scenarios were run using MARXAN (1 000 000 iterations; 100–200 runs; two-step selection process) to derive the most efficient near-optimal reserve configuration. For the selection of primary catchment planning units, boundary length costs were not included in the calculations, because of the relative simplicity of costs, large size of planning units and there being no requirement for connectivity.

For the subcatchment analyses, scenarios were evaluated using on the planning unit cost per hectare, with the best solution based on a combination of the best planning unit cost per hectare as well as the total area needed to secure feature targets. Costs weighted by priority primary catchments and incorporating a boundary length penalty (i.e. a cost added when subcatchments are not adjoining, based on their shared boundary) improved upstream–downstream connectivity and increased selection of subcatchment planning units with primary catchment types. This partial longitudinal connectivity was achieved by including boundary costs for any planning unit boundary that was intersected by either perennial mainstem rivers or wetlands. These boundary lines were assigned a value of 200 m for boundaries for either rivers or wetlands, or a value of 250 m for boundaries common to rivers and wetlands. Boundary length weights of 0.1, 0.5, 1.0 and 10 were used in the scenario analyses. Upstream–downstream connectivity was further enhanced by setting high targets for subcatchments through which diadromous eels (*Anguilla mossambica*) must migrate to reach upper river reaches. The efficiency of existing protected area networks (excluding marine zones) in representing earmarked freshwater areas was examined by comparing the number of planning units within protected areas that were selected as priority subcatchments when no planning units were assigned with a 'conserved' status versus the total number of planning units with a 'conserved' status. The analyses of the conservation plans run with and without protected areas earmarked as 'conserved' indicated that only 31% of the existing protected area network would have been suitable for a freshwater conservation plan, and had no previously defined protected areas in KwaZulu-Natal existed prior to a planning exercise.

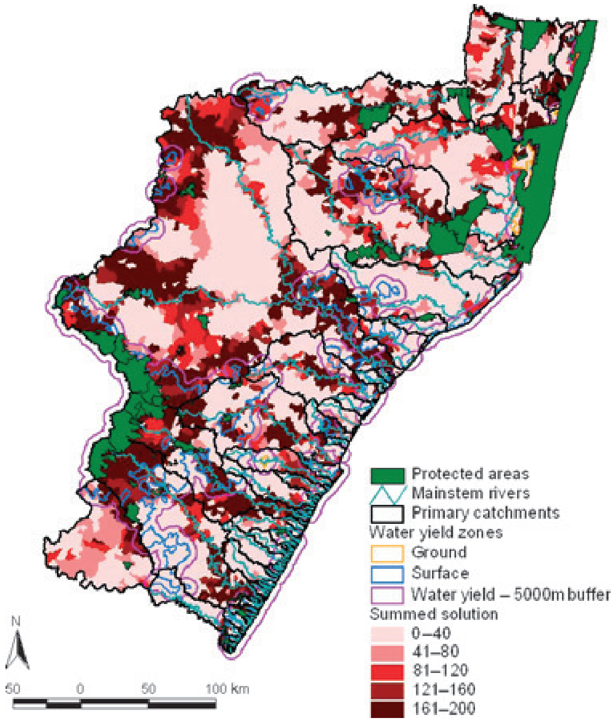


15 **Fig. 4** Priority primary catchments for KwaZulu-Natal based on analyses using the MARXAN conservation planning software.

The summed solution, based on the data inputs, is shown in Fig. 5. In this version, all targets were achieved; given that targets ranged from 15 to 100%, 95% of the 235 features had good redundancy in the plan (i.e. >100% of targets met). Once the near-optimal solution for representation was chosen, further persistence criteria were considered, by incorporating zones that are critical for ecosystem functioning. Management zones were added as the high groundwater and surface water yield zones, with a 5000 m buffer outside these zones as an initial approach to further protecting the integrity of these process zones. The demarcation of a buffer zone is intended to guide development within these areas, to reduce the ecological impacts of unplanned anthropogenic development.

Step 5: implement conservation actions

A first step in implementing conservation actions in a resource-limited environment was to rank priority planning units based on vulnerability versus irreplaceability (Margules & Pressey, 2000). Irreplaceability (defined as the selection frequency from the MARXAN runs: i.e. the number of times a planning unit was selected of a total of 200 iterations and reflected as a percentage) was combined with an indication of vulnerability to assign a priority value to each planning unit, according to eqn 6. Vulnerability was equated with the level of anticipated threat based on surfaces previously developed by Lombard M., Fairbanks D., Goodman P. & Mwicigi J. (unpubl. data) and expressed as a percentage. Subcatchments for



16 **Fig. 5** Summed solution output from MARXAN to achieve targets for freshwater conservation plan in KwaZulu-Natal, with water management zones incorporated, where the higher the summed solution is the greater the conservation priority.

urgent implementation action could be identified using a measure of 'efficiency', adapted from the ideas of Desmet & Berliner (2007), with subcatchments of high priority and low cost preferentially chosen.

$$P = I * V \tag{6}$$

where P is priority; I, irreplaceability; V, vulnerability

The majority of planning units exhibited low selection and vulnerability values, with 996 sites exhibiting high (>80%) irreplaceability scores, of which only 33 of these had high (>50%) vulnerability scores. Where the planning unit priority values were plotted against their associated 'cost' values to provide list of subcatchments where conservation measures could be implemented most efficiently, a total of 77 of 1445 earmarked planning units were identified as critical planning units as a management focus for the next 5 years (Fig. 6).

Discussion

Assessment of the current plan

The two-tiered nested hierarchical approach we used was one solution for ensuring that freshwater conservation planning catered for landscape-level processes and management-scale options at the subcatchment level. Such an approach is gaining popularity amongst freshwater conservation planners, with alternative nested hierarchical approaches which aim to cluster related subcatchments into management units described by Leathwick *et al.* (this issue) and Heiner & Higgins (this issue). Using this approach made

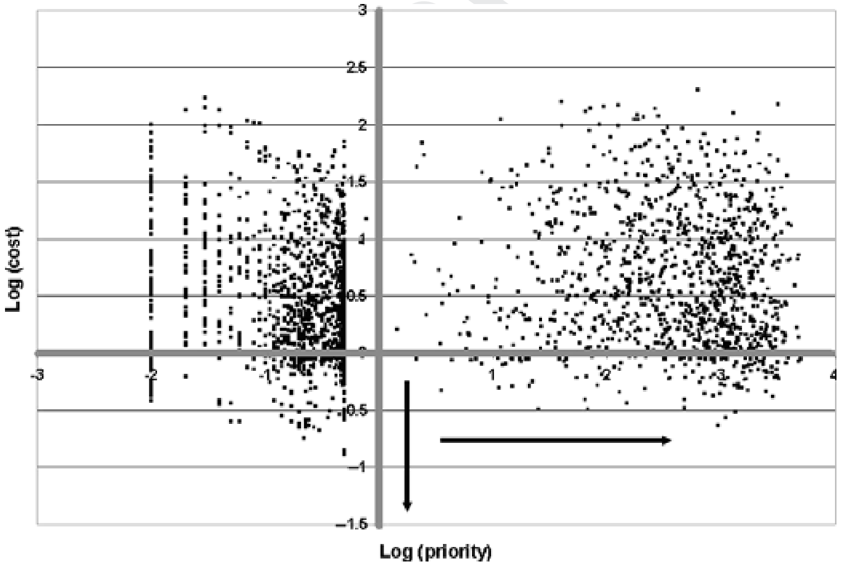


Fig. 6 Scatterplot of priority versus efficiency of 4602 planning units for the KwaZulu-Natal freshwater conservation plan. Subcatchments marked for implementation action are shown by the arrows. 17

explicit the selection of subcatchment planning units that represent the different primary catchment types. The selected configuration therefore promoted the selection of subcatchments within the same primary catchments, which are better connected than subcatchments falling in adjacent primary catchments. At the subcatchment scale, we chose to represent river types in three different categories, and at two different scales. This is because of the assumption that different stream orders reflect different types of aquatic communities. The smaller, less impacted lower order streams are assumed to be in a better condition than the larger mainstream rivers, serving as refugia for freshwater biodiversity. Integrated freshwater conservation planning should not only recognise the role of tributaries as refugia, but also plan for a network of tributaries linked to mainstem rivers, which act as movement corridors.

The most efficient scenario was based on the inclusion of weighted boundary length costs and area-weighted costs. Given the number of possible solutions (2^{4602}), the range of scenarios run provided an indication of the sensitivity of the final model to the different cost weightings and targets. Upstream–downstream connectivity was achieved when planning unit and boundary length costs were equivalent. Inclusion of species that have wide habitat ranges and depend on large-scale processes is a further useful technique of incorporating landscape-level processes, as was shown through the inclusion of eels to enhance upstream–downstream connectivity. The inclusion of terrestrial conservation priorities as costs provided a practical means of integrating terrestrial and freshwater conservation plans.

We recognise that the cost approach used in this article does not reflect the true economic costs in implementing a regional aquatic conservation plan. In its current form, the costs indirectly reflect economics, because smaller land parcels will have lower purchase, management and rehabilitation costs than larger land parcels. Implicit in this approach is that these values nevertheless represent opportunity costs for commercial development if land is reserved for biodiversity conservation (Margules & Pressey, 2000). The purpose of the current cost approach is to assist in producing a spatial layer of priority ecosystems, which forms the basis for a conservation authority to negotiate with additional competing stakeholders and land users. A dialectic process should be followed from this point, which incorporates actual economic costs as a post-conservation planning exercise. This was recently illustrated in preliminary discussion with representatives from South Africa's multimillion dollar trout industry. Such representatives are better placed to define the economic and social implications of implementing the aquatic conservation plan to their sector, and it would have been both premature and naïve for the conservation authority to assign costs without due consultation with competing resource users.

Fewer alternative options are provided in the conservation plan when high targets are set for selected features. In the majority of cases where lower targets are set, alternative spatial options exist because of over-achievement of targets, taking due cognizance of catchment condition. Redundancy in target achievement provides the basis for negotiating alternative spatial configurations which still meet conservation targets without alienating stakeholders from other economic sectors. In this freshwater conservation plan, much of the flexibility in the plan is through the relatively high number of river types and lower targets, while the high leverage and fine-tuning came through the species features and their associated targets.

Within the current conservation scenario, all targets could be met because of the decision not to exclude degraded planning units. The strength of this approach is that current condition does not drive the selection of priority subcatchments and ultimately implementing agencies can select and prioritise freshwater conservation planning units based on their desired ecological status, with appropriate management actions taken to resolve any discrepancies between present and future desired ecological status. Such management approaches can be further refined by using a contextual map of other priorities – for example, social and economic needs and priorities (Naidoo *et al.*, 2006), patterns of irreplaceability and vulnerability (Linke *et al.*, 2007), or return on investment studies (Wilson *et al.*, 2007).

Future research priorities to refine the plan

The current freshwater conservation plan is the first version of a systematic conservation plan specifically aimed at addressing freshwater biodiversity issues in KwaZulu-Natal. Within current national legislation, this plan should be revised at least every 5 years, where it is anticipated that there will be changes made to the plan itself, as data improve and thinking on the river type classification and other data layers advance. We assume that developments within conservation planning software will be aimed more directly at freshwater conservation planning, and in particular address the issue of connectivity in river systems more explicitly. It is also possible that our fledgling attempts to integrate freshwater and terrestrial conservation planning will lead to more nearly optimal solutions for integration. However, given the speed of land use transformation (1.8% per annum on average between 1994 and 2005 for the coastal – 10–30 km inland – region of KwaZulu-Natal; D. Jewitt, Pers. Comm.), the urgent application of this plan into tangible results should also provide the opportunity to measure management efficiency in the next iteration of this plan.

One of the inherent weaknesses in the plan is in the type and number of species selected. A gap in the species list is the incomplete consideration of aquatic macroinvertebrates. Given the overwhelming number of undescribed invertebrate species, and their high relative abundances, one way to remedy this could be to focus on key groups such as Trichoptera, Simuliidae, Plecoptera and Ephemeroptera that respond to hydrological alterations and represent the full spectrum of functional feeding groups (de Moor, 2002; Schael & King, 2005; Heino & Soininen, 2007). Also, understanding the relative contribution of non-perennial river types to biodiversity is inadequate.

The species list chosen ultimately reflects collecting and taxonomic bias, and skewed scales of distributional ranges, which could be addressed using non-linear predictive environmental modelling techniques (e.g. Castella *et al*., 2001; Linke *et al*., 2007). Inherent in such an approach is the further validation of the existing river type classification with biodiversity surveys. A further complementary issue is to identify further ecotones (confluences, hot springs and waterfalls) and understand their significance in ecological processes.

Current impacts that threaten the persistence of biodiversity have been factored into the plan through consideration of land transformation within the province. This is a simplistic measure that infers information about water use, sedimentation and chemical and nutrient pollution. However, more direct measures of current impacts that evaluate the ecological integrity of freshwater ecosystems, such as water quality and quantity indicators and biotic indicators, are available and should be more explicitly incorporated where possible (see, for example, O'Keeffe *et al*., 1987). In addition, an assessment of future threats to the persistence of freshwater biodiversity, and the generation of best- and worst-case scenarios, should be examined and incorporated more explicitly. Socio-economic issues such as human population pressures, estimated water demands and allocations, planned dams and interbasin transfers are important in this regard, as well as the future risks of climate change. Such factors should be integrated into a more holistic catchment transformation index and an updated threats layer. These endeavours need to recognise the broader context of ensuring functional linkages between the different components of the water cycle (e.g. rivers and groundwater linkages) and recognising that identified reserves are inadequate on their own to protect freshwater systems (Barmuta *et al*., this issue). Given that many catchments in South Africa are already in a state of water stress, climate change predictions have implications for the ability of aquatic ecosystems to adapt. It is therefore important that the impact of climate change on freshwater ecosystems is accounted for and documented to investigate possible adaptive measures for these possible projections.

This plan could be expanded to include important social and economic information. Explicit evaluation of the costs and benefits of conserving subcatchments on environmental flows and thus the amount water available for allocation to competing sectors would greatly assist decision-makers in integrated water resources management. In addition, sites of cultural significance could be included into the cost surface to favour alignment of natural and social heritage goals.

Connectivity is dealt with here in a static, spatial form and does not capture its temporal dimension. The temporal dimension of flow regimes is of critical importance: for example, inadequate flows at certain times of the year resulting from over-abstraction of water can inhibit important ecological processes such as spawning; flow regulation can cause discontinuities to floodplain backwaters. It is difficult to incorporate this temporal element explicitly into a map. However, rivers flagged as a priority for conservation should be accompanied by management guidelines aimed at ensuring that both spatial and temporal connectivity is maintained or restored to the system.

Another issue still to be addressed is that of defining defendable feature targets. Systematic conservation planning for terrestrial systems uses island biogeography theory and species–area curves to set defendable conservation targets (Desmet & Cowling, 2004). This same approach cannot be applied to river systems, and the current approach was based on 20% for all mainstem river types and wetland types, and 15% target for the 1 : 50 000 tributaries. An approach with a theoretical grounding similar to the species–area curve is necessary for setting meaningful targets in freshwater conservation planning. Being longitudinal segments, river length is an equivalent to area. Segment lengths and their location become the critical determinants in choosing how much of a river should be conserved. One possible approach could be to base targets on established measures of species diversity (Whittaker, 1972) and river ecology theory. The location of highest alpha diversity, as related to the river continuum concept, and species turnover along a river's longitudinal axis (beta diversity), determine where and how long a river segment should be to conserve maximum species diversity. Between-river diversity (gamma diversity) determines how many river systems should be conserved within each biome, and this relies on a suitable river classification system. Such an approach encompasses spatio-temporal variability and would incorporate ecological processes operating at different scales along environmental gradients (Ward & Tockner, 2001).

These future research priorities highlight the fact that conservation plans remain a negotiating tool between different competing stakeholders. Irrespective of how conceptually advanced such plans are, uncertainty nevertheless remains unavoidable. Planners need to learn to deal explicitly with such uncertainty (Margules & Pressey, 2000), and adaptively learn from it. Ultimately, the success of any conservation plan is in its translation from blueprint to conservation action and management plan (Groves, 2003).

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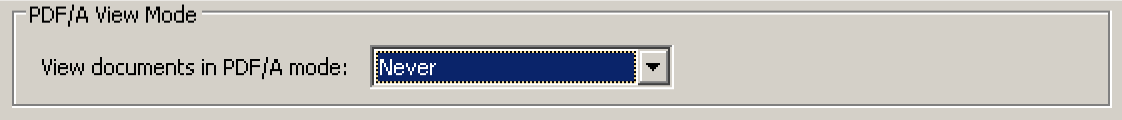
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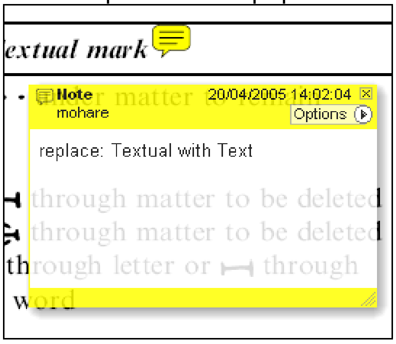

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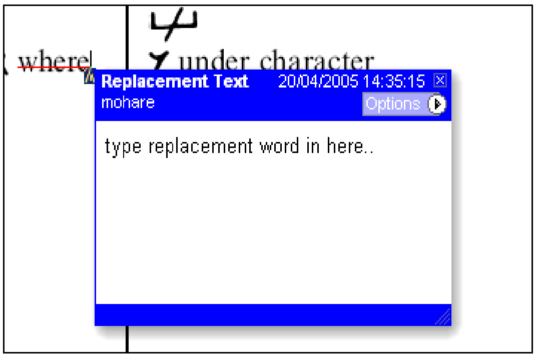

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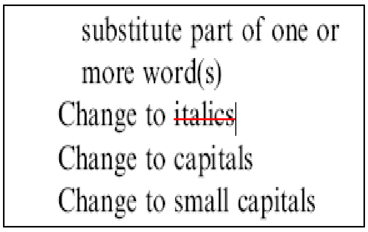
Strikes through text in a red line.


substitute part of one or
more word(s)
Change to ~~italics~~
Change to capitals
Change to small capitals

How to use it:

1. Select cursor from toolbar
2. Highlight word or sentence
3. Right click
4. Select Cross Out Text

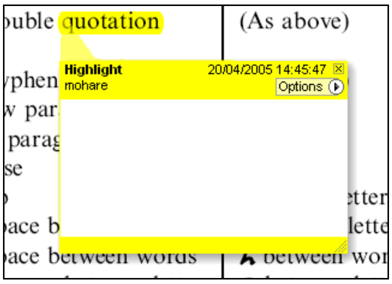
Approved tool — For approving a proof and that no corrections at all are required.

How to use it:

1. Click on the Stamp Tool in the toolbar
2. Select the Approved rubber stamp from the ‘standard business’ selection
3. Click on the text where you want to rubber stamp to appear (usually first page)

Highlight tool — For highlighting selection that should be changed to bold or italic.

Highlights text in yellow and opens up a text box.

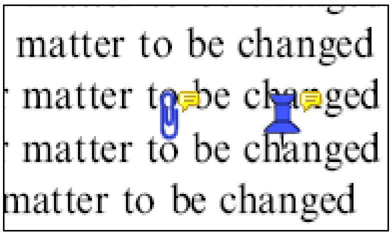


How to use it:

1. Select Highlighter Tool from the commenting toolbar
2. Highlight the desired text
3. Add a note detailing the required change

Attach File Tool — For inserting large amounts of text or replacement figures as a files.

Inserts symbol and speech bubble where a file has been inserted.

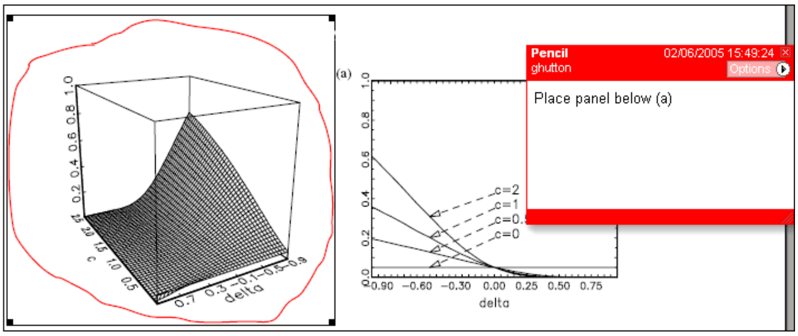


How to use it:

1. Click on paperclip icon in the commenting toolbar
2. Click where you want to insert the attachment
3. Select the saved file from your PC/network
4. Select appearance of icon (paperclip, graph, attachment or tag) and close

Pencil tool — For circling parts of figures or making freeform marks

Creates freeform shapes with a pencil tool. Particularly with graphics within the proof it may be useful to use the Drawing Markups toolbar. These tools allow you to draw circles, lines and comment on these marks.



Place panel below (a)

How to use it:

1. Select Tools > Drawing Markups > Pencil Tool
2. Draw with the cursor
3. Multiple pieces of pencil annotation can be grouped together
4. Once finished, move the cursor over the shape until an arrowhead appears and right click
5. Select Open Pop-Up Note and type in a details of required change
6. Click the X in the top right hand corner of the note box to close.

Help

For further information on how to annotate proofs click on the Help button to activate a list of instructions: