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Designing protected areas to conserve riverine biodiversity: Lessons from a hypothetical redesign of the Kruger National Park

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ABSTRACT

The process of designing protected areas to represent all ecosystems in an area adequately is becoming increasingly sophisticated. To date freshwater aquatic ecosystems have seldom been considered in this process. How much of a difference does it make when they are considered as well?

This study examined the conservation of riverine biodiversity within 17 assessment units contained by the catchment areas of five perennial rivers flowing through Kruger National Park and two seasonal rivers that are largely contained within this park. Physical river types, fish species and invertebrate families or genera were used as surrogates of riverine biodiversity. Conservation planning software was used to select an optimal set of planning units to represent and maintain riverine biodiversity.

The current spatial configuration of Kruger National Park, largely an accident of history, is particularly poor when assessed against the objective of conserving riverine biodiversity. Several alternative layouts are examined. These options are theoretical since there is little current opportunity to reassign land uses in the region. This study shows that substantially improved layouts for both riverine and terrestrial biodiversity are possible, under the constraint of the same total area under protection. The study also shows that even these optimal layouts are only partially successful in efforts to conserve fully representative samples of riverine biodiversity. Because of the longitudinal connectivity of rivers, conservation strategies that extend beyond protected areas are essential. Explicit conservation visions, targets and strategies need to be included in integrated water resource management plans.

Based on the results of this study, nine recommendations are provided for increasing the effectiveness of current and future protected areas in conserving riverine biodiversity. These are to use systematic conservation planning to make biodiversity benefits explicit; mend the disconnect between terrestrial and freshwater conservation; use multiple

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surrogates wherever possible; be strategic about the collection and management of primary data; strive for maximum hydrologic connectivity; resist development pressure; foster good relationships across park fences; where relevant, pursue multi-national cooperation at the basin scale; and engage the value debate and resolve awareness and capacity constraints.
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1. Introduction

Human efforts, especially over the past 50 years, to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel have resulted in an array of extensive changes to terrestrial, freshwater, and marine ecosystems. These changes, in turn, have resulted in an ongoing, widespread, and largely irreversible loss in the number and variety of organisms on Earth as well as the degradation of ecosystem services (Millennium Ecosystem Assessment, 2005). The effects of pressures that arise from social and economic aspirations have been particularly severe on freshwater ecosystems. An index of the world's freshwater species shows a more rapid decline between 1970 and 2000 than for terrestrial and marine indices during the same period (World Wide Fund For Nature, 2004). Similarly, South Africa's first National Spatial Biodiversity Assessment examined the terrestrial, river, estuarine, and marine environments, and highlighted the fact that the country's river ecosystems are now in a much poorer state overall than its terrestrial ecosystems (Driver et al., 2005; Nel et al., 2007).

Protected Areas represent one management instrument to balance the conservation and use of natural resources. The process of designing Protected Areas so that they are more fully representative of the ecosystems of the world has become progressively more sophisticated (Lovejoy, 2006). However, Protected Areas do not seem to be as effective for conserving aquatic biota as they are for terrestrial biota (Cowx, 2002; Crivelli, 2002; Impson et al., 2002; Nel et al., 2007). This situation persists because few models of good Protected Area design exist and traditional notions of Protected Areas translate imperfectly to the freshwater realm (Abell et al., 2007). At least three factors contribute to this dilemma.

First, few Protected Areas have been established specifically to conserve freshwater biodiversity (Crivelli, 2002). There are exceptions: Saunders et al. (2002) list a few examples where protected areas have been established specifically to protect freshwater species and habitats, and Roux et al. (2002) show how river diversity was given special emphasis in planning the expansion of the Greater Addo Elephant National Park in South Africa. Most protected areas have been designed to conserve terrestrial biodiversity features, and freshwater ecosystems have been addressed incidentally (Skelton et al., 1995).

Second, the length of most rivers and the size of their catchment area make it difficult to include both the headwaters and lower reaches within a Protected Area. A river not fully contained within a Protected Area remains vulnerable since impacts that take place outside the Protected Area can still have negative consequences for freshwater biodiversity within the Protected Area (Saunders et al., 2002). A good example of this situation is provided by Kruger National Park (Kruger, hereafter), South Africa's flagship national park. Rivers in the region of Kruger flow from the west to the east, whilst the park is oriented north-south. This means that all the major rivers flow into and out of the park, rather than being contained within the park.

Third, even rivers within Protected Areas are not necessarily conserved in terms of their structural and functional components. Rivers in Protected Areas are often impounded to secure drinking water for terrestrial species (Gaylard et al., 2003), while the construction of roads, bridges, and tourist lodges on the banks of rivers contribute to habitat degradation (Water Research Commission, 2001). Although it is less likely that these kinds of activities and their associated impacts will occur today, the legacy of past impacts still remains with society.

For Protected Areas to contribute meaningfully to the conservation of riverine biodiversity, a shift is needed both in the way protected areas are designated and, once rivers have been included, how the rivers within these areas are managed. The objective of this paper is to advance understanding of the relationship between the design of Protected Areas and the representation and persistence of riverine biodiversity within such areas of statutory protection. The current spatial design of Kruger is compared with an idealized or hypothetical configuration that is optimized for conserving riverine biodiversity. Based on the results of this case study, recommendations are presented for increasing the effectiveness of Protected Areas for conserving riverine biodiversity, either through the expansion of existing Protected Areas or through the improved design of new Protected Areas.

2. Materials and methods

2.1. *Study area*

The study area is situated in the north-eastern corner of South Africa (Fig. 1), bounded by the Crocodile River in the south, the Luvuvhu River in the north, the border between South Africa and Mozambique in the east, and the upper limits of the drainage boundaries of the Crocodile, Sabie, Olifants (including its tributary the Blyde River but excluding the Olifants River catchment upstream of its confluence with the Blyde River), Letaba and Luvuvhu Rivers in the west. The upper Olifants catchment is excluded because it falls within a different geo-climatic region and is therefore not representative of the study area. However, for assessing the potential for biodiversity features associated with the lower reaches of the Olifants River to persist, the influence of the upper Olifants catchment was considered. In addition to the five perennial rivers that flow through Kruger, two seasonal drainage

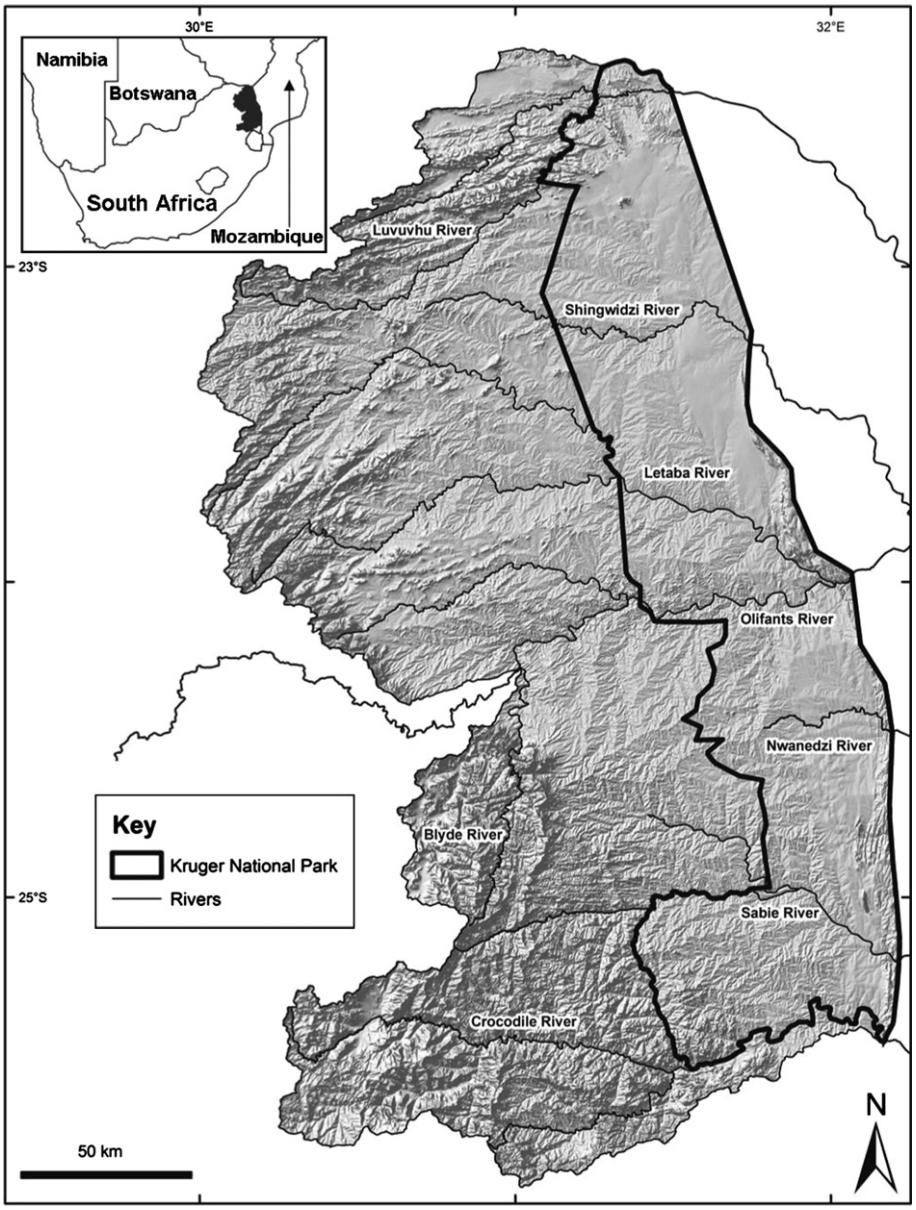

Fig. 1 – Map of the study area showing major rivers and Kruger National Park. Inset shows the location of the study area within southern Africa.

systems that are largely contained within the park, namely the Shingwidzi and Nwanedzi rivers (Fig. 1), were included in this study.

The Drakensberg escarpment in the west (over 1800 m.a.s.l.) descends steeply to an elevation of approximately 500 m.a.s.l. at its foothill zone to the west of the western border of Kruger, followed by a gentler gradient to the east. The gently undulating terrain in this zone (the "Lowveld") descends gradually to an elevation of approximately 450 m.a.s.l. at the western margin of the Lebombo Mountains, which forms the eastern boundary of Kruger and the boundary between South Africa and Mozambique.

Mean annual rainfall decreases from over 1500 mm/annum along the escarpment crest to less than 500 mm/annum on the eastern border of Kruger (Pollard et al., 2003). Most rainfall (>95%) is received as discrete thunderstorm events during the austral summer months (October–March). Summer months are characterized by warm to hot and wet to humid conditions, while the winter months are cool and dry.

The study area covers approximately 57,000 km^2, of which about 19,000 km^2 (33%) falls within the park. Kruger has an average west-to-east width of 60 km, a north-south distance of 350 km and has a 1050 km boundary. All the perennial rivers that form part of this study arise in mountainous terrain outside Kruger and flow through the park in an easterly direction. These rivers are important sources of water for sustaining the heterogeneity and ecosystem processes in Kruger (Gaylard et al., 2003).

Based on rivers digitized at 1:500,000 scale, the total river length within the study area is approximately 8500 km. Of this, almost 2600 km (31%) lies within Kruger, while a further 300 km (3%) form the borders of Kruger. Based on the same

data set, over 5100 km of the rivers in the study area comprise Strahler first-order streams (Lanfear, 1990). Approximately 1700 km of these first-order rivers lie within Kruger.

2.2. Assessment units

Tertiary drainage regions or catchments, which form part of the standard hierarchical divisions (primary to quaternary) used for water resource management in South Africa (Midgley et al., 1994) were used as assessment units in this study. As an example, two primary river systems flow through the study area, namely Limpopo and Incomati. The main tributaries of the Incomati form secondary catchments, of which the Sabie and Crocodile rivers are located in the study area. A further division, usually along significant tributaries within a secondary catchment, demarcates tertiary catchments of which Crocodile has four and Sabie three.

2.3. Representation

A coarse-and-fine filter surrogate approach is recommended as the most robust method of representing biodiversity (Lombard et al., 2003). Physical river types were used as coarse filter biodiversity surrogates for representing riverine biodiversity. Coarse filter surrogates focus on conserving higher levels of the biodiversity hierarchy, such as river types or vegetation types, assuming that this allows the conservation of many common species and communities, the ecological processes that support them and the habitats in which they occur and evolve over time (Hunter, 1991). Using coarse filter ecosystem types also offers a rapid and pragmatic approach for conservation planning in data-poor regions (Thieme et al., 2007). Coarse filter river types were supplemented with distribution data for focal fish species and focal invertebrate genera as fine filter biodiversity surrogates.

Quantitative conservation targets were set for representation of each biodiversity surrogate. For river types, targets were set as 20% of the total length of each river type within the study area, based on recommendations by the World Conservation Union's Caring for the Earth Strategy (The World Conservation Union, 1991). This is also the conservation target currently supported by a national process for freshwater ecosystem conservation (Roux et al., 2006). For focal fish species and focal invertebrate genera, a target of at least one "viable" population was set. Here, "viable" was judged using expert opinion and was interpreted as a reproducing and self-maintaining population.

2.4. Physical river types

Three GIS layers were superimposed to derive river types (Fig. 2): river ecoregions (Kleynhans et al., 2005), hydrological flow types (Hannart and Hughes, 2003), and geomorphological river zones (Rowntree and Wadeson, 1999).

The rivers of South Africa have been segmented into a set of distinctive river ecoregions (Kleynhans et al., 2005), following the hierarchical ecoregional typing approach of Omernik (1987). River ecoregions represent regions within which there is relative similarity in the mosaic of ecosystems and ecosystem components (biotic and abiotic, aquatic and terrestrial).

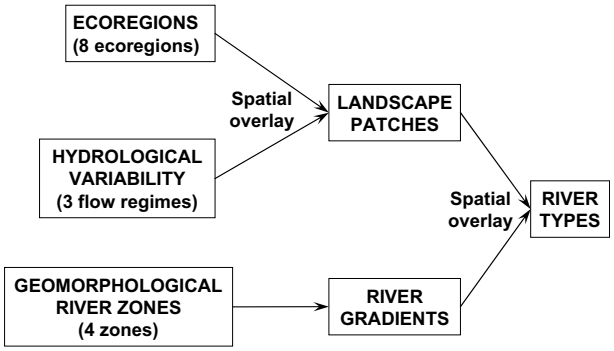

Fig. 2 – The process used for generating river types. Landscape patches, described by ecoregions (Kleynhans et al., 2005) and hydrological variability (Hannart and Hughes, 2003), were combined with geomorphological river zones of individual streams (Rowntree and Wadeson, 1999) to delineate 33 distinct river types.

Rivers grouped together in a particular ecoregion are more similar to one another than to rivers in other ecoregions. The study area contains eight of the 31 level 1 river ecoregions in South Africa.

The hydrological index (HI; Hannart and Hughes, 2003) quantifies in a single statistic the temporal variability of river flows and was used to distinguish between three river flow regimes, namely: perennial (HI = 1–4), seasonal (HI = 5) and ephemeral (HI = 6–9).

The third input used to derive physical river types is the geomorphological river zone. The derivation of these zones was based on the hierarchical model proposed by Rowntree and Wadeson (1999) for geomorphological classification of river channels in South Africa. The required data were obtained using a semi-automated GIS procedure and the NASA 90 m × 90 m resolution Shuttle Radar Topography Mission Digital Elevation Model (United States Geological Survey, 2003). For this study, the seven possible geomorphological zone classes from Rowntree and Wadeson (1999) were condensed into four classes, consisting of (i) mountain streams, (ii) upper foothills, (iii) lower foothills, and (iv) lowland rivers.

2.5. Fish species

Fish distribution data were compiled from databases of the former Transvaal Provincial Administration, the national River Health Programme (see www.csir.co.za/rhp), Kruger National Park, South African Institute for Aquatic Biodiversity, and Albany Museum. Distribution records ranged from the first half of the 1900s to as recent as 2004. Data manipulation involved the elimination of records with doubtful geographic coordinates and the removal of records for alien species and marine species (including the Zambezi shark, *Carcharhinus leucas*, found in the lower Luvuvhu River). Non-riverine fish species (*Nothobranchius* spp. and *Protopterus* spp.) found in small ephemeral floodplain pans along the eastern boundary of Kruger were also excluded from this study.

Developing conservation strategies that focus on all species is impractical, and it is standard practice in conservation planning to focus on a subset of species and ecosystem types

which serve as surrogates for meeting the needs of all species (Lambeck, 1997; Margules and Pressey, 2000). Using this concept, a subset of fish species was selected as focal species for deriving a conservation design for the freshwater fish species of the Lowveld. These focal species were selected on the basis of their uniqueness in terms of isolated populations, regional endemism, ecotone specialization (for example inhabiting a particular band along the west-east altitude and temperature gradient), or environmental requirements that would also be representative of a range of other species (for example clear and fast-flowing streams).

2.6. *Invertebrate families and genera*

Family-level invertebrate data were compiled from River Health Programme surveys conducted on the Crocodile (1993–1996; 1999), Sabie (1993–1995; 1997; 1999), Olifants (1993–1995; 1998–1999; 2003–2004), Letaba (2000–2001; 2003–2004), and Levuvhu (1999; 2003) river systems. Invertebrates were sampled according to the South African Scoring System described in Chutter (1998), and specifically versions 4 and 5 of the method, referred to as SASS4 and SASS5 (Dickens and Graham, 2002), respectively. Most of the data were collected during the low-flow season that corresponds to the dry winter months of March to October in the study area. Data from a total of 210 sites were analyzed. Fifty-three of these sites are located on the Crocodile, 66 on the Sabie, 16 on the Olifants, 33 on the Letaba, and 42 on the Levuvhu river systems.

In addition, the Albany Museum database on freshwater invertebrates was queried for distributional data of all taxa recorded within the study area. These data date back to river surveys conducted between 1954–1965 and 1983–1986 (Moore and Chutter, 1988), and also include later surveys conducted in 1990 and 2003. Collecting methods included the sampling of a range of aquatic biotopes as well as occasional collection of adult insects with light traps, under lights at night or in the daytime with handnets. The distribution records of an identified set of genera (reflecting species in many instances) were selected from the orders Ephemeroptera, Odonata, Plecoptera, Trichoptera, and Diptera (Simuliidae).

Focal families and focal genera were selected from the respective data sets for use as fine-filter surrogates for the invertebrates of the Lowveld on the basis of their rarity in collections, their need for specific ecological conditions (thus making the genera an indicator of those conditions), or where the species could be used as an indicator of a particular biogeographical distribution pattern.

2.7. *Hydrologic connectivity*

Three qualitative measures of hydrologic connectivity (Freeman et al., 2007) were used as surrogates for considering the likely persistence of riverine biodiversity: longitudinal and lateral connectivity of riverine systems, the inclusion of catchments that yield relatively high volumes of runoff, and temporal connectivity (based on land-use patterns and associated flow and water quality modifications) expressed as the potential risk of biodiversity loss during the three driest months of a year when river flows are lowest.

Longitudinal connectivity was simply taken as the degree to which upstream and downstream reaches are included in a conservation design, while lateral connectivity was based on the inclusion of whole tertiary catchments to protect the aquatic-terrestrial gradients from river to watershed. Runoff estimates within the study area were based on the national data set used by Driver et al. (2005).

Risks to aquatic biodiversity persistence were evaluated in terms of water availability and the load of total dissolved salts for each quaternary catchment for the three driest months of the year. Risk increased as water availability declined and/or salt loads increased – the higher the risk, the lower the ability of that catchment to allow aquatic biodiversity to persist in the long term. Catchments with the lowest risk of biodiversity loss during the three driest months of the year provide opportunities for the highest persistence of aquatic biodiversity. Water availability in each quaternary drainage area was calculated as the sum of river flow (Midgley et al., 1994) less the water abstracted for each type of off-channel use (Department of Water Affairs and Forestry, 1996a). The load of total dissolved salts from each land-use during the three driest months of the year was obtained by multiplying the volumes of effluent from each category of land-use by the characteristic median total dissolved salts concentrations for that effluent type, derived from the national pollution monitoring programme (Department of Water Affairs and Forestry, 1996a). Comparison of the concentrations of total dissolved salts with water quality guidelines (Department of Water Affairs and Forestry, 1996b) provided an estimate of the "acceptability" of the water for aquatic ecosystems.

2.8. *Spatial design for representing Lowveld riverine biodiversity*

Our approach for representing the variety of riverine biodiversity within the study area is broadly based on the framework proposed by Ward and Tockner (2001), whereby alpha, beta and gamma diversity are arrayed hierarchically across river reaches, catchments, and the larger study area. To maximize the capture of alpha, beta, and gamma diversity, we used a conservation planning tool (C-Plan; Pressey et al., 1993) which applies the principle of complementarity to design an optimal set of assessment units to meet representation targets, and hence turnover of biodiversity. A second principle, conservation efficiency, was used to optimize economy of space, where we aim to meet conservation targets in a design that achieves minimum area (Sarkar et al., 2006). We examined conservation efficiency by comparing the number of river types and focal fish species adequately represented within Kruger, with a spatial design of similar size to the park configured using C-Plan. This was achieved in C-Plan by selecting sequentially the planning unit with the highest summed irreplaceability, based on conservation targets for river types and focal fish species. Here, a river type or focal fish species achieving 75–100% of its conservation target was regarded as adequately represented. The threshold of 75% acknowledges that conservation targets of many biodiversity features could be fully met in a relatively small area. However, 100% achievement of conservation targets for all features was found to be very area-expensive. This finding is consistent with a number of similar

conservation planning studies (Montgomery et al., 1994, 1999; Ando et al., 1998; Polasky et al., 2005).

We also considered the implications of this riverine spatial design for conserving terrestrial biodiversity, using vegetation types as coarse-filter surrogates. First, the number of vegetation types (Mucina and Rutherford, 2004) adequately represented by the riverine spatial design was compared to the number adequately represented in Kruger. Targets developed for a recent national spatial biodiversity assessment (Driver et al., 2005) were used to assess the adequacy of representation of each vegetation type, where vegetation types achieving 75–100% of its conservation target were considered adequately represented. Secondly, we compared the number of vegetation types adequately represented by the riverine spatial design, with a terrestrial spatial design, based only on vegetation types. This was achieved in C-Plan by selecting sequentially the planning unit with the highest summed irreplaceability, based on conservation targets for vegetation types only.

3. Results

3.1. Assessment units

Following tertiary catchment boundaries, the study area was subdivided into seventeen assessment units that ranged in size from 1450 to 5450 km^2, with an average size of about 3350 km^2 (Fig. 3). From north to south, and starting with the five perennial rivers, Luvuvhu River contributed two units (LUV1, LUV2), Letaba River three (LET1, LET2, LET3), Olifants River three (OLI1, OLI2, OLI3), Sabie River three (SAB1, SAB2, SAB3), and Crocodile River four units (CRO1, CRO2, CRO3,

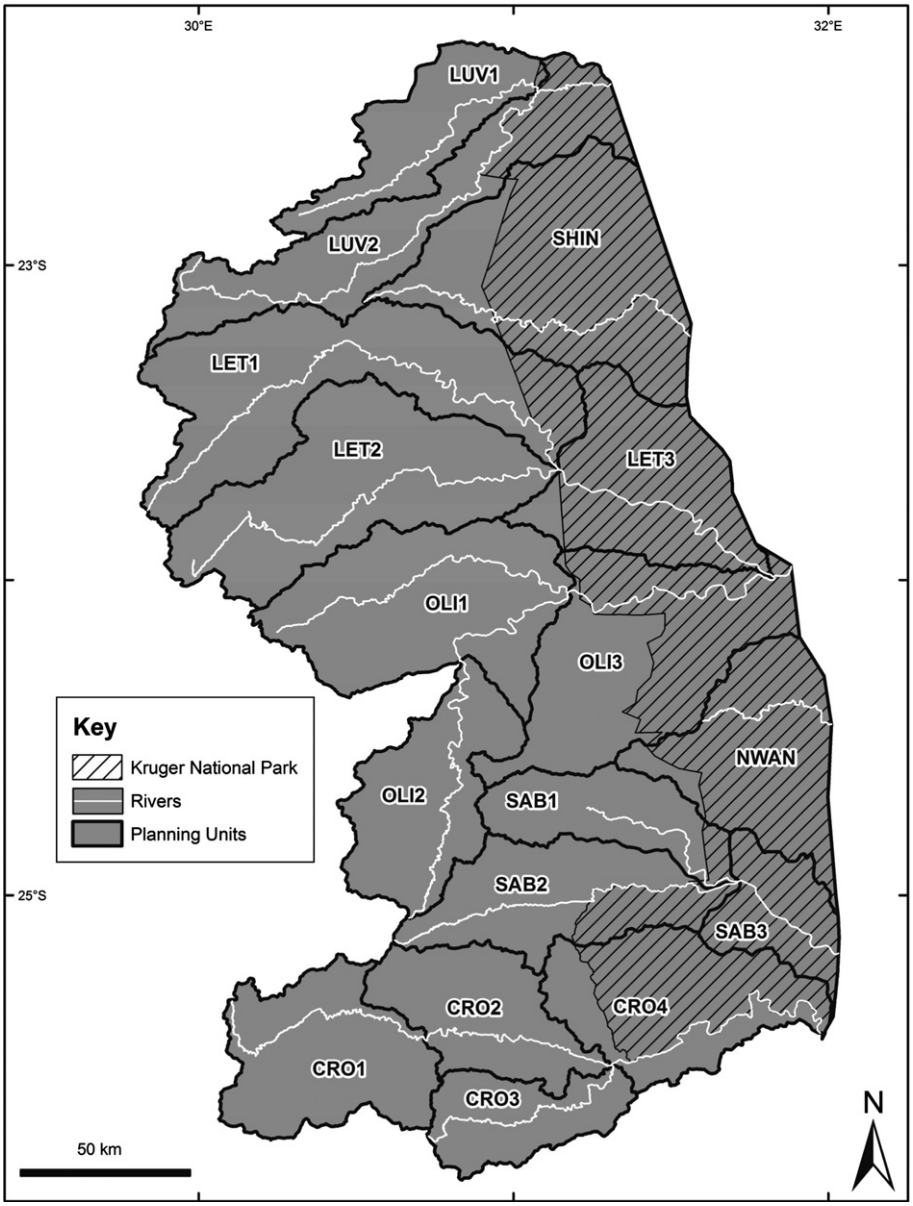

Fig. 3 – The 17 assessment units comprising the study area. Only main rivers are shown, i.e. not all the rivers that were used for the assessments in this paper.

Table 1 – Occurrence of river types within the study area, expressed as percentage of the length of a river type in each assessment unit

River types	Assessment units																
	LUV1	LUV2	SHIN	LET1	LET2	LET3	OLI1	OLI2	OLI3	NWAN	SAB1	SAB2	SAB3	CRO1	CRO2	CRO3	CRO4
Eastern Bankenveld-P-MS	0	0	0	4	0	35	0	8	0	0	0	0	0	53	0	0	0
Eastern Bankenveld-P-UF	0	0	0	0	0	0	0	46	0	0	0	0	0	54	0	0	0
Limpopo Plain-P-LR	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lebombo Uplands-E-LF	0	0	6	0	0	0	0	0	0	76	0	0	18	0	0	0	0
Lebombo Uplands-E-MS	0	0	0	0	0	0	0	0	0	**100**	0	0	0	0	0	0	0
Lebombo Uplands-E-RJ	0	0	0	0	0	0	0	0	0	**100**	0	0	0	0	0	0	0
Lebombo Uplands-E-UF	0	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lebombo Uplands-P-LF	0	0	0	0	14	0	0	0	31	0	0	0	37	0	0	0	18
Lebombo Uplands-P-UF	0	0	0	0	29	0	0	0	0	0	0	0	71	0	0	0	0
Lowveld-E-LF	0	0	41	6	5	4	3	0	16	18	0	3	0	0	0	0	4
Lowveld-E-MS	0	0	12	7	0	0	21	0	30	6	0	0	0	0	0	0	24
Lowveld-E-UF	0	0	25	2	2	14	0	0	6	27	0	14	0	0	0	0	10
Lowveld-P-LF	1	4	0	11	11	14	14	4	15	0	7	5	5	0	0	0	9
Lowveld-P-LR	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lowveld-P-MS	0	22	0	2	2	6	3	8	5	0	10	13	10	0	0	0	20
Lowveld-P-RJ	0	21	0	0	0	0	0	38	0	0	0	0	0	0	42	0	0
Lowveld-P-UF	0	21	0	7	3	6	18	2	7	0	12	8	2	0	10	0	4
Lowveld-S-LF	0	0	0	82	0	0	0	0	0	0	0	0	0	0	0	0	17
Lowveld-S-MS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**100**
Lowveld-S-UF	0	0	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0
Northeastern Highlands-E-MS	0	0	0	0	0	74	0	0	0	0	0	26	0	0	0	0	0
Northeastern Highlands-P-LF	0	0	0	81	0	0	0	0	0	0	0	0	0	0	0	19	0
Northeastern Highlands-P-MS	0	1	0	15	0	14	10	1	0	0	9	24	0	0	16	10	0
Northeastern Highlands-P-RJ	0	0	0	0	0	0	0	51	0	0	0	0	0	0	49	0	0
Northeastern Highlands-P-UF	0	0	0	17	0	11	1	0	0	0	1	23	0	0	26	21	0
Northern Escarpment Mountains-P-MS	0	0	0	0	0	4	9	26	2	0	3	12	0	19	18	6	0
Northern Escarpment Mountains-P-UF	0	0	0	0	0	0	0	32	0	0	0	4	0	53	10	0	0
Northern Escarpment Mountains-P-MS	0	0	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0
Soutpansberg-E-MS	0	0	**100**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soutpansberg-P-LF	61	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soutpansberg-P-MS	55	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soutpansberg-P-RJ	28	72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Soutpansberg-P-UF	5	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Names of river types are expressed in an ecoregion-flow type-geomorphic zone convention, with the flow types being perennial (P), seasonal (S), and ephemeral (E); and the geomorphic zones being mountain streams (MS), upper foothills (UF), lower foothills (LF), and lowland rivers (LR). River types confined to a single assessment unit are indicated in bold.

Table 2 – Distribution of fish species in the study area

Fish species	Assessment units																
	LUV1	LUV2	SHIN	LET1	LET2	LET3	OLI1	OLI2	OLI3	NWAN	SAB1	SAB2	SAB3	CRO1	CRO2	CRO3	CRO4
*Amphilius natalensis**	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	0	0
*Amphilius uranoscopus**	1	1	0	0	1	0	1	1	1	0	1	1	0	1	1	1	0
Anguilla bengalensis labiata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Anguilla marmorata	0	1	1	0	1	1	0	0	1	0	0	1	1	0	0	1	1
Anguilla mossambica	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1
Aplocheilichthys johnstoni	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Awaous aeneofuscus	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Barbus afrohamiltoni	0	1	1	1	1	1	1	0	1	0	1	1	1	0	0	0	1
Barbus annectens	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
Barbus anoplus	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	0	0
*Barbus argenteus**	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0
Barbus bifrenatus	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
*Barbus brevipinnis**	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0
Barbus eutaenia	1	1	0	0	1	0	1	1	1	0	1	1	1	0	1	1	1
Barbus lineomaculatus	1	1	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0
Barbus mattozi	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0
*Barbus motebensis**	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
*Barbus neefi**	1	1	0	0	1	0	1	1	1	0	0	0	0	1	1	0	0
Barbus paludinosus	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1
Barbus radiatus	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	0	1
Barbus toppini	0	1	1	1	1	1	1	0	1	0	1	1	1	0	0	0	1
Barbus treurensis*	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0
Barbus trimaculatus	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Barbus unitaeniatus	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1
Barbus viviparus	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	1
Brycinus imberi	1	1	1	0	1	1	0	0	1	1		1	1	0	0	0	1
*Chiloglanis anoterus**	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0
*Chiloglanis bifurcus**	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Chiloglanis paratus	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	1
*Chiloglanis pretoriae**	1	1	1	1	1	0	1	1	1	0	0	1	0	1	1	1	1
*Chiloglanis swierstrai**	0	1	0	1	1	1	1	0	1	1	1	1	1	0	0	1	1
Clarias gariepinus	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
Glossogobius callidus	0	1	1	1	1	0	1	0	1	0	1	1	1	0	0	0	1
Glossogobius giuris	0	1	0	1	0	1	1	0	1	0	1	1	1	0	0	0	1
Hydrocynus vittatus	0	1	1	0	1	1	0	0	1	0	0	1	1	0	0	0	1
Kneria auriculata*	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0
Labeo congoro	1	1	1	0	0	1	1	0	1	1	0	1	1	0	1	0	1
Labeo cylindricus	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Labeo molybdinus	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Labeo rosae	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	1
Labeo ruddi	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1
Labeobarbus marequensis	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
*Labeobarbus polylepis**	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0

(*continued on next page*)

Table 2 – continued

Fish species	Assessment units														
	LUV1	LUV2	SHIN	LET1	LET2	LET3	OLI1	OLI2	OLI3	NWAN	SAB1	SAB2	SAB3	CRO1	CRO2	CRO3	CRO4
Marcusenius macrolepidotus	1	1	0	0	1	1	0	1	1	1	1	1	1	0	1	1	1
Mesobola brevianalis	0	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1
Micralestes acutidens	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
*Opsaridium peringueyi**	1	1	0	0	0	0	1	1	1	1	1	1	1	0	1	1	1
Oreochromis mossambicus	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Petrocephalus wesselsi	1	1	0	0	1	1	1	1	1	0	1	1	1	0	1	0	1
Pseudocrenilabrus philander	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Schilbe intermedius	1	1	1	1	1	1	0	0	1	0	1	1	1	0	0	0	1
*Serranochromis meridianus**	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Synodontis zambezensis	0	1	1	1	0	1	1	0	1	0	0	1	1	0	0	0	1
Tilapia rendalli	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Tilapia sparrmanii	1	1	0	1	1	1	1	1	1	0	0	1	0	1	1	0	1
*Varicorhinus nelspruitensis**	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0

Focal fish species are indicated with an asterisk. Focal species endemic to a single assessment unit are indicated in bold; 1 indicates presence and 0 indicates absence.

CRO4). The two seasonal rivers that are largely contained within Kruger, namely Shingwedzi and Nwanedzi Rivers, contributed one assessment unit each (SHIN, NWAN).

3.2. *Representation*

The spatial overlay of eight ecoregions, three flow types and four geomorphological river zones resulted in 33 distinct river types within the study area (Table 1). Collation of fish records indicated the presence of 56 native riverine species in the study area. Of these, 16 were identified as focal species and their distribution across the assessment units were recorded (Table 2). For invertebrates, 19 focal families and 25 focal genera (Table 3) were identified.

River types and focal fish species exhibit a moderate turnover among planning units, with nine (27%) river types and two (13%) focal fish species occurring in only a single assessment unit (Tables 1 and 2, respectively). Focal invertebrate genera exhibit a more ubiquitous distribution at the scale of these analyses: only three focal genera are confined to a single assessment unit (Table 3). Representational analysis found that only two assessment units (LUV1, SAB1) are required for representing focal invertebrate families and four assessment units (LUV2, OLI3, SAB1, CRO1) for focal invertebrate genera (Table 3). Our results showed little congruence between units required for focal families and those required for focal genera. Due to the incongruence between family and genus level invertebrate data, neither were included in determining conservation priorities, though we assessed the extent to which the focal invertebrate genera were captured by a conservation design for river types and fish.

3.3. *Hydrologic connectivity*

Kruger has a particularly poor design for conserving ecosystem processes associated with longitudinal river connectivity. The park has no direct control over water and catchment management practices upstream or downstream (in Mozambique) of its borders. This situation is worsened by the park being located in the driest part of the study area, with the high water yielding parts of the catchment located along the western boundary of the study area (Fig. 4). Only one tertiary-level drainage region (SAB3) is contained within the boundaries of Kruger.

The potential risk envelopes (Fig. 5) identify and help to prioritize areas where future conservation activities would offer the highest level of persistence as a function of current land and water use. Most of the high risk areas experience a combination of high-density rural populations, intensive irrigation, and high return flows from irrigated agriculture; these areas offer bleak prospects for conserving the full spectrum of biodiversity structure and function.

3.4. *Spatial design for representing Lowveld riverine biodiversity*

To achieve the representation target for the nine river types that are confined to a single assessment unit requires the selection of assessment units LUV2, SHIN, LET1, NWAN, and CRO4. A further two assessment units (LET3, OLI2) are

Table 3 – Distribution of invertebrate genera/species of special concern in the study area

Invertebrate genera/species of special concern	Assessment units																
	LUV1	LUV2	SHIN	LET1	LET2	LET3	OLI1	OLI2	OLI3	NWAN	SAB1	SAB2	SAB3	CRO1	CRO2	CRO3	CRO4
Simulium lumbwanum	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Acanthiops varius	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Afrobaetodes berneri	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0
Centroptiloides bifasciata	1	1	0	0	1	1	1	0	0	0	0	1	1	1	1	0	0
Demoreptus natalensis	0	1	0	0	0	1	1	0	1	0	0	0	1	0	0	0	1
Pseudopanota maculosa	1	1	0	0	0	1	0	0	0	0	0	1	1	1	1	0	1
Barnardara demoori	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0
Dicercomyzon sp.	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Adenophleboides patriciae	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Machadorhythus sp.	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Elassoneuria spp.	1	1	0	0	1	0	0	0	1	0	0	1	1	1	1	0	0
Oligoneuropsis elizabethae	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Prosopistoma spp.	0	0	0	0	0	0	1	0	1	0	0	1	1	1	1	1	1
Chlorocypha spp.	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Metacnemis sp.	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Neoperla spio	1	1	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1
Calamoceratidae (*Anisocentropus* sp.)	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dipseudopsis sp.	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	0	0
***Psychomyiellodes* spp.**	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0
Aethaloptera sp.	0	1	0	0	1	0	0	0	1	0	0	1	1	0	0	0	1
Catoxyethira spp.	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
Lepidostoma sp.	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Ceraclea (Pseudoleptocerus)	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0
Setodes sp.	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0
Paduniella sp.	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Species/genera endemic to a single assessment unit are indicated in bold; 1 indicates presence and 0 indicates absence.

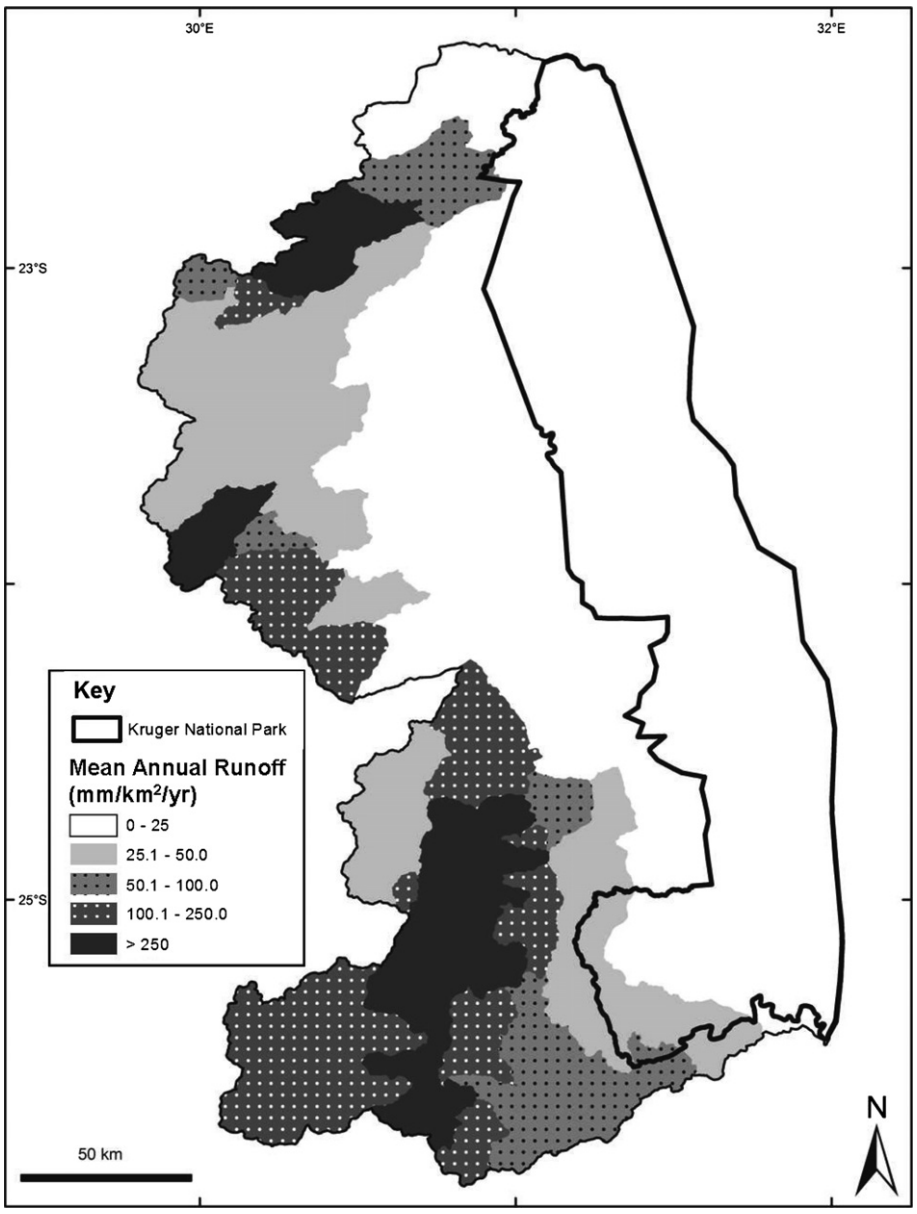

Fig. 4 – Map of the study area showing the distribution of high and low runoff catchments, based on the national data set used by Driver et al. (2005).

required to represent all river types. A preferred design to selecting LET3 and OLI2 – one that is less space-efficient, but which ensures representation of all river types and better supports longitudinal connectivity – would be to select the three units of the CRO1, CRO2, SAB3 (Fig. 6).

It is possible to represent the 16 focal fish species in only four assessment units (OLI2, SAB2, SAB3, CRO1; Fig. 6); these units also represent 53 of the 56 fish species native to the study area. If we exclude the species confined to OLI2 (species 7) from the Protected Area design (adopting off-site conservation strategies for this species), then SAB2, SAB3, and CRO1 would provide representation of 15 focal species and 50 species native to the study area. These assessment units form a conveniently clustered riverine conservation area. A possible shortcoming of the spatial conservation design for fish is that it falls entirely in the Incomati River basin and therefore does not cater for potential diversity in genetic lineages across the Incomati-Limpopo divide (Wishart and Davies, 2003).

A combined design for representation of river types and focal fish species (Fig. 6) requires nine assessment units (LUV2, SHIN, LET1, NWAN, CRO1, CRO2, CRO4, SAB2, SAB3) within the border of the idealized Protected Area, and management of one assessment unit (OLI2) outside the border. This design also represents 24 of the 25 focal invertebrate genera, excluding one species that is confined to OLI3 (*Barnardara demoori*, Order Ephemeroptera, Family Caenidae). The combined riverine spatial design offers much better longitudinal as well as lateral connectivity than is the case with Kruger, requiring an area of approximately 31,000 km^2. Kruger currently represents 58% of the riverine biodiversity features

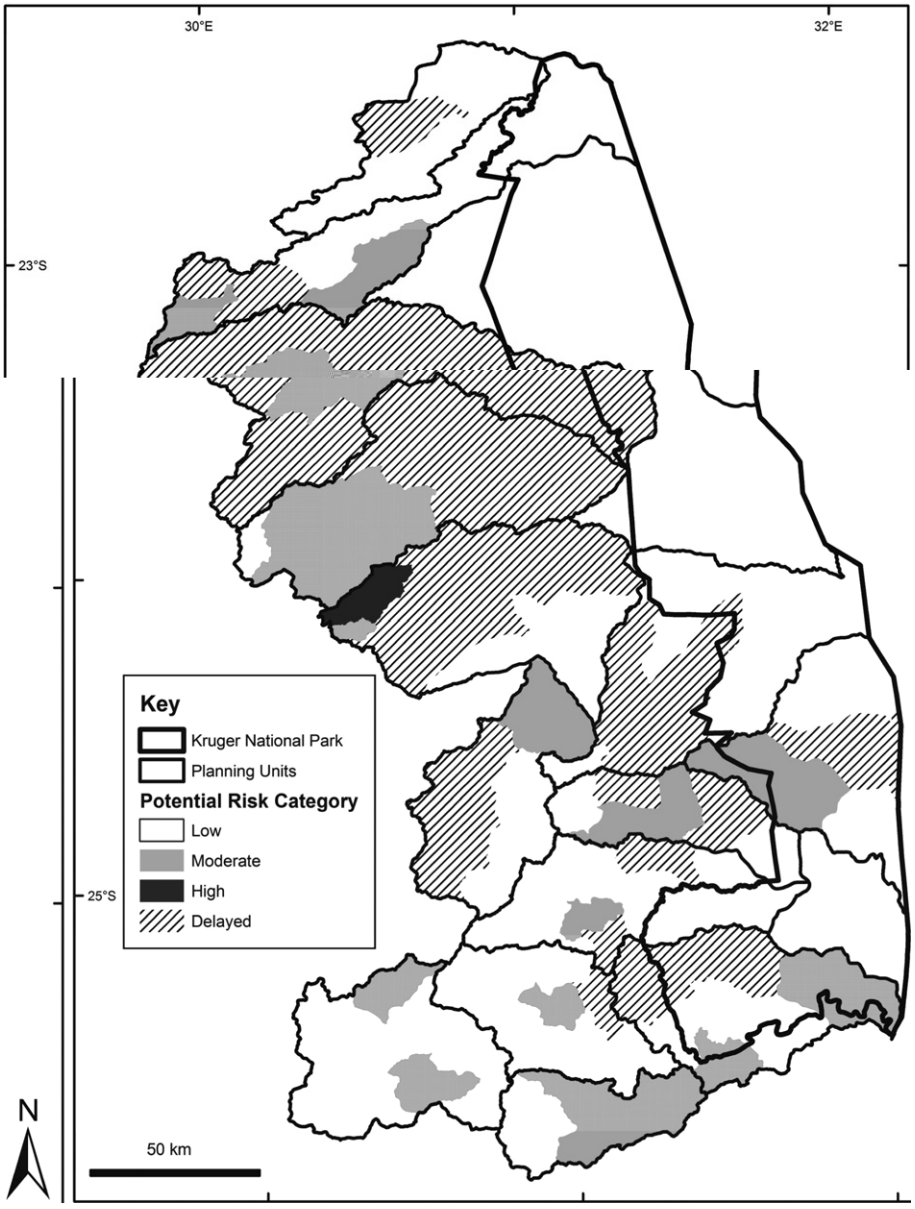

Fig. 5 – Map of the study area showing distribution of drainage areas that pose different levels of risk to the persistence of habitat (in terms of water quantity and water quality), and thereby risk to the persistence of freshwater biodiversity during the three driest months of the year (July–September). The interpretation of the different risk categories is as follows: *Low:* Low risk that the habitat persistence will be compromised. Adequate water available and total dissolved salts concentrations are less than 100 mg/l. *Moderate:* Moderate risk that habitat persistence will be compromised due to potential low volumes of water and total dissolved salts concentrations between 100 and 1000 mg/l. *High:* High risk that persistence (of suitable habitat) will be compromised due to low to very low volumes of water and high potential total dissolved salts concentrations (1000–3000 mg/l). *Delayed:* High risk that habitat persistence will be compromised due to high potential total dissolved salts concentrations (3000 mg/l), though the absence of flow during the dry season delays the expression of this risk. Commencement of river flows at the onset of the rainy season (October) mobilizes the accumulated salts along the length of these river segments.

(river types and fish species) adequately; with prior planning this figure could have been increased to 76% for the equivalent area encompassed within Kruger (Fig. 7a). The "improved" design is also more efficient than the existing Kruger for representing vegetation types. Approximately 58% of the vegetation types within the study area are adequately represented compared to only 43% within Kruger. A spatial design based solely on vegetation types is only marginally more efficient at conserving terrestrial species than one based solely on riverine features, adequately representing 63% of the vegetation types of the planning region (Fig. 7b), as opposed to 58% using the riverine criteria (Fig. 7a).