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Approaches to the selection of a network of freshwater ecosystems within New Zealand for conservation

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Abstract

1. Although the freshwater environments of New Zealand once comprised an extensive interconnected network of rivers, lakes, and wetlands, their extent, condition, and connectivity have been reduced since human settlement, with consequent impacts on ecosystem functioning and the species that reside within them. An imbalance in the protection of freshwater ecosystems, with significant under-representation of lowland freshwater ecosystems, makes these the most threatened ecosystems in New Zealand.
2. Recent policy initiatives are attempting to take a whole-catchment view, i.e. 'from the mountains to the sea'. There is also an increased focus on the restoration of vulnerable water bodies that still support moderate values, in preference to previous long-term restoration programmes for the most degraded freshwater sites. The outcomes of these programmes have been less certain, with opportunities lost for systems that are declining in condition but have not yet reached the threshold of degradation for investment.
3. This work demonstrates the gains that can be made through the use of spatial conservation prioritization software to identify priority catchments for freshwater restoration, emphasizing the representation of a full range of ecosystems and species, while also taking account of longitudinal-connectivity constraints within catchments.
4. Third-order subcatchments were the most suitable scale for this prioritization, to capture the most important components within the largest river catchments. Populations of important native fish populations and the locations of major terrestrial conservation projects were also considered when assessing priorities; iteratively chosen weightings were applied to control the balance of representation across these different features.
5. Consideration was also given to existing patterns of protection, in order to assess the biodiversity representation within areas currently protected and to identify sites that would provide maximum additional benefits if restored or protected.
6. The resulting subcatchment prioritizations have contributed strongly to regional collaborative restoration processes.

KEYWORDS

agriculture, catchment, fish, invertebrates, land drainage, modelling, restoration, river, watershed

1 | INTRODUCTION

Although approximately one-third of the total land area of New Zealand is formally protected for conservation or similar purposes, as in many other countries (Hermoso, Abell, Linke, & Boon, 2016; Margules & Pressey, 2000), the distribution of protected lands is biased strongly towards cold, steep or super-humid environments that are unsuitable for economic uses such as agriculture or forestry. As a result, warm dry lowland environments are severely under-represented (Figure 1; Leathwick, Overton, & McLeod, 2003). This, coupled with a historical focus on terrestrial or marine protected areas, has resulted in the highly uneven representation of freshwater habitats within the current protected area network of New Zealand, a disparity also noted in other jurisdictions (Pittock et al., 2015). As a consequence, although many rivers in New Zealand have their headwaters within conservation land, their middle and lower reaches often flow through intensively developed landscapes, which generally have high nutrient yields from agriculture (Snelder, Larned, & McDowell, 2018). Further disparities in representation have arisen from the drainage of once-extensive lowland wetlands, with total losses of at least 90% (Ausseil, Chadderton, Gerbeaux, Stephens, & Leathwick, 2011). An increase in the area of wetlands in protected areas was noted between 1990 and 2013, although many of the gains were in high-altitude areas (>500 m a.s.l.), with swamps, fens, and marshes remaining under-represented in protected areas (Robertson, 2016). More recent estimates of the rate of loss in wetland extent in the Southland region of New Zealand show 0.5% loss per year (Robertson, Ausseil, Rance, Betts, & Pomeroy, 2018).

These marked biases in protection and degradation pose considerable challenges to the Department of Conservation (DOC) of New Zealand, which has the core central government responsibility for biodiversity conservation, as set out in the Conservation Act 1987. Its management programmes are guided by a set of statements of corporate intent that reflect the need to protect a full range of ecosystems, while also ensuring the persistence of threatened species (Department of Conservation, 2016). A more specific freshwater goal identifies a target of restoring 50 freshwater ecosystems 'from the mountains to the sea' (national target 11; Department of Conservation, 2016). These operational goals are derived more broadly from the Biodiversity Strategy (New Zealand Central Government Coordinating Group for Biodiversity, 2000), a policy statement produced to meet international obligations under the various treaties to which New Zealand is a signatory. For example, Aichi Biodiversity Target 11 requires that 'at least 17 percent of terrestrial and inland water areas...are

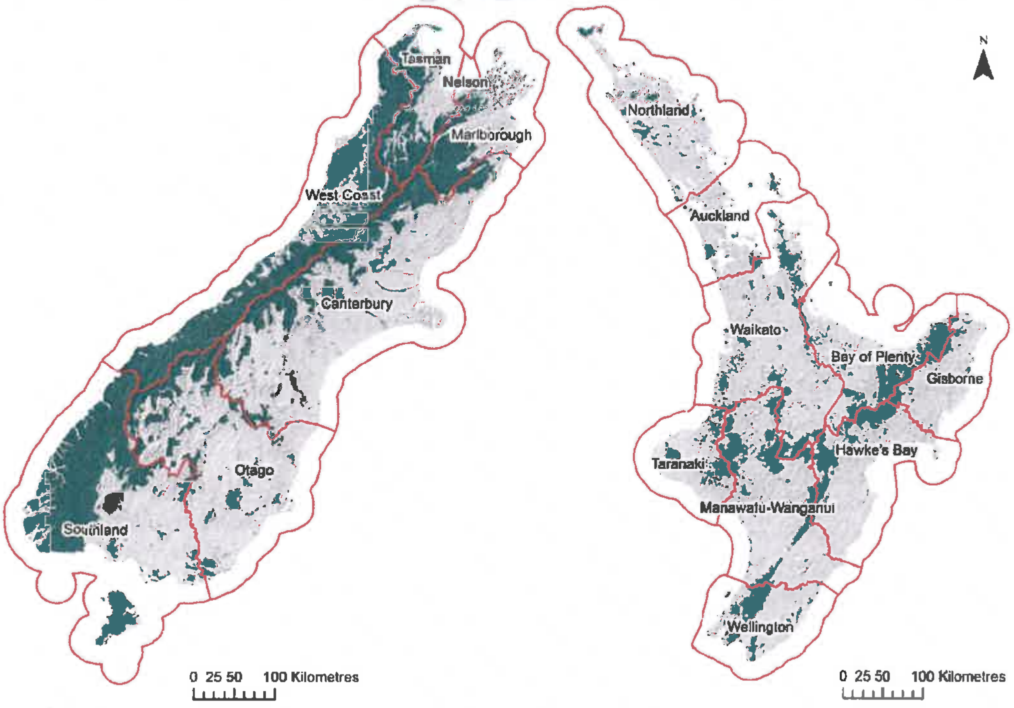

FIGURE 1 Protected Area Network – New Zealand (PAN-NZ) as of 2014. Note: for clarity, regions referred to in the text are shown but marine areas are not shown

conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas…' (Convention on Biological Diversity, 2010). In an assessment in 2014, 29% of river lengths in New Zealand were within protected areas (Department of Conservation, 2014); however, the broader legislative and policy framework provides few mechanisms to address the major freshwater protection imbalances between upland and lowland environments in New Zealand (New Zealand Conservation Authority, 2011). Historically, New Zealand rehabilitation funding has focused on expensive, long-term programmes in the most severely damaged freshwater sites, where rehabilitation is far more difficult to achieve than it would be for other catchments declining in condition that have not yet reached the same levels of degradation (Table 1).

Identifying streams, rivers, wetlands, springs, and lakes that still retain a high degree of ecological integrity in highly modified lowland landscapes is particularly challenging for managers, and more so given the DOC's stated intent to restore the integrity of entire catchments. An early attempt at identifying such sites under DOC's Waters of National Importance programme listed an initial set of candidate rivers for enhanced conservation protection, (Chadderton, Brown, & Stephens, 2004). Following improvements in data quality and the use of the spatial conservation prioritization software ZONATION (Leathwick, Moilanen, Ferrier, & Julian, 2010; Moilanen et al., 2005), separate lists of high priority rivers, lakes, and wetlands were publicly released and circulated to management agencies as spatial features and supporting publications in 2010 as Freshwater Ecosystems of New Zealand (FENZ) (Department of Conservation, 2010; Leathwick, West, Moilanen, & Chadderton, 2012). Although there have been regular requests for FENZ from universities, regional councils, and consultancies, and some limited application of the information by central government agencies, there has been little progress in systematically achieving better protection of a representative range of freshwater ecosystems at a national level.

This paper describes research initiated by a management agency designed to identify candidate sites in which to implement both protection and restoration work aligned with the DOC's goal of restoring freshwater ecosystems at a whole-catchment scale. This direct path to implementation addresses a common shortfall of conservation assessments (Knight et al., 2008). In contrast to previous analyses that separately prioritized rivers, lakes, and wetlands, this prioritization explicitly considers linkages across these three realms. Emphasis was given to achieving the representation of a full range both of ecosystems and threatened fish species, using ecosystem classifications contained in the FENZ database, together with additional spatial data for species and management sites held by the DOC. The approach taken here incorporates the benefits of including data describing species locations (Esselman & Allan, 2011), the consideration of connectivity between freshwater ecosystems (Nel, Reyers, Roux, & Cowling, 2009; Nel, Reyers, Roux, Impson, & Cowling, 2011), the benefits of existing restoration projects (Linke, Turak, & Nel, 2011), and the generation of prioritizations suitable for use in engaging with local communities (Boon, 2000). Comparable catchment evaluations and prioritizations are increasingly being used to inform freshwater conservation in a number of other countries (Boon, Holmes, Maitland, & Fozzard, 2002; Howard et al., 2018; Nel et al., 2011), and the prioritizations here follow the comprehensive, adequate, representative, and efficient (CARE) principles, which are judged to be the most effective planning approach for freshwater conservation (Linke et al., 2011).

TABLE 1 Effect of varying connectivity settings on the representation of freshwater ecosystems in the top 30% of sites (columns 2–4), and the mean variability of ranks within catchments with extents greater than 10 000 ha, as measured by their standard deviation

Connectivity setting	Rivers	Lakes	Wetlands	SD
Weak	0.70	0.65	0.67	0.198
Moderate	0.68	0.67	0.64	0.190
Strong	0.67	0.67	0.63	0.185
Severe	0.66	0.67	0.62	0.184
Severe	0.66	0.67	0.62	0.184

2 | METHODS

2.1 | Design considerations

Designing a prioritization approach at a whole-catchment scale ('from the mountains to the sea') while also achieving the representation of a full range both of ecosystems and species is particularly challenging, largely because of complications of scale. In particular, the biologically tuned river ecosystem classification contained in FENZ identifies classification membership at the scale of individual river segments, i.e. sections of river between two adjacent confluences. As a consequence, when using this classification, all of the mid- to large-sized river catchments in New Zealand contain a number of river ecosystem types, e.g. small first-order headwater streams distant from the coast, second- and third-order tributaries at intermediate elevations, the main river stem, and lowland tributaries close to the coast. Selecting priority lakes and wetlands is more straightforward, as these typically form discrete spatial entities, which the FENZ database categorizes using a geomorphological classification for lakes, and a hydrological, soil, and vegetation-based classification for wetlands.

In addition to these issues of scale, consideration is also required of the longitudinal connectivity that is a major driver of ecological integrity within river systems, with the condition of ecosystems in the lower catchment being driven strongly by conditions in their upstream headwaters (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). Conversely, the ecological integrity (Schallenberg et al., 2011) of ecosystems in the upper catchment can also be influenced greatly by the condition of the downstream catchment, a factor of particular importance in the rivers of New Zealand, given the significant role played in them by diadromous (migratory) fish species (McDowall, 1998).

Given these two constraints, a stage-wise prioritization approach was implemented that aimed to identify interconnected sets of catchments and subcatchments that collectively maximize the representation of a full range of river, lake, and wetland ecosystems, while also considering the distributions of selected non-migratory and migratory fish species. Specific consideration was given to: (i) the estimation of ecological integrity, so that all other things being equal, examples of particular river, lake, or wetland ecosystems in good condition were selected ahead of those in poor condition; and (ii) the potential to gain leverage from work on terrestrial biodiversity conservation undertaken by the DOC, assuming that the management of catchment cover to a high level of condition for the benefit of terrestrial species is also likely to benefit freshwater ecosystems. Consideration was also given to the practical constraints imposed by the uneven patterns of biodiversity representation provided by the existing protected area network in New Zealand.

2.2 | Prioritization approach

All freshwater prioritizations were calculated using the spatial conservation planning software ZONATION (Moilanen et al., 2005; Moilanen et al., 2012), which provides options designed explicitly to accommodate the constraints imposed by longitudinal connectivity in aquatic ecosystems (Moilanen, Leathwick, & Elith, 2008). Information used in ZONATION consists of gridded data layers, with one layer describing the spatial distribution of each biodiversity feature of interest – in this case a river, lake, or wetland ecosystem. During prioritization, grid cells are removed in a backwards stepwise fashion, with the grid cell(s) making the lowest contribution to the representation of a full range of biodiversity features being removed first. When grid cells have been grouped into planning units, all cells located within the lowest value planning unit are removed at the same time, rather than the removal occurring cell by cell. The outputs from the prioritization analysis include gridded maps showing the variation in biodiversity priority across the landscape of interest, and tabular data describing the protection provided to each biodiversity feature as a function of site priority. Priorities are expressed in this analysis on a 0–1 scale, with the top 10% of sites having values in the range 0–0.1, the next highest 10% of sites having values in the range of >0.1–0.2, and so on. In broad terms this means that if the management goal is to protect or manage the top 10% of sites, then management should be applied to all sites with scores of 0.1 and below.

Because of the complexity of analysis, prioritizations were developed in a stage-wise process, starting with an initial basic analysis using information on the distribution of river, lake, and wetland ecosystems, and their condition. Other components were then added progressively, with their weights assessed and tuned to ensure a satisfactory balance between them and the layers already included in the analysis.

2.3 | Updated estimates of river (catchment) pressures

River and stream condition estimates are calculated by combining individual terms describing the effects of nitrogen pollution, catchment clearance, the impervious surfaces associated with urbanization, industrial and mining discharges, dams, and introduced fish (Leathwick & Julian, 2007). Before calculating any prioritizations in this analysis, the river and stream condition estimates contained in FENZ were updated in two ways. First, updated estimates were obtained of instream nitrogen concentrations, calculated recently using land-use data from 2008 with the SPARROW model (S. Elliot, pers. comm.), and providing a more accurate assessment of the effects of recent land-use intensification in lowland parts of New Zealand (Clapcott et al., 2012). Second, to improve the overall discrimination of river pressures resulting from land-use intensification, the calculation of stream condition (*EI*) contained in FENZ was altered to allow for an interaction between catchment clearance and nitrogen inputs, i.e.

$$EI = minimum\left(EI_{impervious}, EI_{native}{}^{0.8*}\, EI_{nitrogen}{}^{0.8}, EI_{mines}\right)^{*} EI_{dam}{}^{*}\, EI_{fish},$$

where the individual terms describe the ecological impacts (*EIs*) of impervious surfaces, loss of native cover in the catchment, nitrogen inputs, mine and industrial discharges, dam-induced alteration of river flows and impedance of upstream/downstream migration, and predation/competition effects from introduced fish species. The addition of an interaction between catchment cover and nitrogen inputs improved the discrimination between catchments that lack indigenous cover but that have low to moderate nitrogen inputs (e.g. under drystock farming or exotic plantations), and those with complete catchment clearance and high levels of nitrogen input resulting from more intensive land management (e.g. intensive agriculture). The use of exponents with a value of 0.8 for these two terms controls the effects of this interaction, generating values for different combinations of catchment clearance and nitrogen inputs; lowest values (i.e. highest ecological impacts) occur in catchments that are both completely cleared of their former native cover and have high instream nitrogen levels, but values increase (i.e. impacts decrease) if either or both of these pressures are reduced in intensity.

2.4 | Calculating initial priorities

For initial prioritization, a set of 100-m resolution gridded or raster data layers was created to represent each of the river and stream, wetland, and lake ecosystems. River and stream ecosystems were described using the 100 groups recognized in Level Two of the FENZ river classification (Leathwick et al., 2011), wetlands were described using the eight groups recognized in the FENZ wetland classification, and lakes were described using 10 geomorphological groups based on the classification of Lowe and Green (1987), i.e. aeolian, geothermal, glacial, landslide, peat, riverine, shoreline, tectonic, and volcanic lakes, together with dams and reservoirs. Separate condition layers were created by writing out the updated river and stream condition estimates (described above) and the FENZ wetland and lake condition estimates as gridded layers with the same resolution and spatial extent as the ecosystem layers.

Longitudinal connectivity between river subcatchments was accounted for using settings in ZONATION that recognize that the biodiversity values of any subcatchment depend not only on the biodiversity features that occur within it and on their condition, but also on the condition and status of the subcatchments to which they are connected along the river network (Moilanen et al., 2008). These constraints act by reducing the value of a target subcatchment as its upstream or downstream subcatchments are removed during the backwards removal process, favouring the allocation of high ranks to interconnected groups of subcatchments. Consideration of downstream connections was only applied to subcatchments occurring within close to moderate distances from the coast, i.e. sufficient for migratory fish to be a significant component of their biodiversity.

The subcatchments used as planning units in this analysis were based on the third-order subcatchment layer contained in FENZ. Subcatchment data were edited extensively to ensure that all subcatchment linkages were correctly specified, and that subcatchment polygons around larger lakes were correctly defined. An accompanying text file specified the linkages between subcatchments, allowing ZONATION to construct the full set of catchment linkages at the outset of each analysis.

Settings used to penalize subcatchments for the removal of the upstream and downstream subcatchments to which they are connected were based on a sensitivity analysis in which penalties were varied while assessing: (i) the resulting representation of a full range of river ecosystems; and (ii) variation in ranks across (interconnected) subcatchments occurring within large catchments (>10 000 ha). Weights were set to maintain a high level of representation across all river ecosystems, while favouring the selection of interconnected sets of subcatchments. These penalties reduced the value of river, lake, and wetland ecosystems to 25% of the original when one-third of the upstream subcatchments were removed, to 12.5% when two-thirds of the upstream subcatchments were removed, and to zero when all of the upstream subcatchments were removed. Three levels of penalties were applied to river ecosystems for the removal of downstream subcatchments, depending on their average distance from the coast. Coastal river ecosystems, i.e. those of greatest importance for migratory fish, received the greatest penalties for the loss of their downstream connections, declining to 50% of their original value when one-third of their downstream subcatchments were removed, to 25% when two-thirds of their downstream subcatchments were removed, and to 33% when all downstream subcatchments were removed. River ecosystems occurring at more inland locations, but still within the distances penetrated by one or more migratory fish species, received less severe penalties, declining respectively to 75, 50, or 0% of their original value, when one-third, two-thirds, or all of their downstream subcatchments were removed, respectively. Inland river ecosystems, i.e. occurring generally at distances from the sea greater than those normally penetrated by migratory fish, were not penalized for the removal of their downstream subcatchments.

2.5 | Adding non-migratory fish distributions

This initial prioritization was expanded by adding data describing the distributions of native non-migratory fish species, mostly galaxiids, including some of the most critically threatened freshwater fish species in New Zealand (Goodman et al., 2014; Appendix S1). Q6 These contribute a significant component to spatial variation in freshwater biodiversity patterns that is largely independent of environmental conditions. Therefore, their distributions are not well captured by the FENZ river classification, which was tuned to the distributions of more mobile migratory fish species and macro-invertebrates (Leathwick et al., 2011). A spatial dataset of recorded locations for threatened freshwater macro-invertebrates was considered for inclusion, but was rejected because of concerns regarding variation both in sampling coverage and taxonomic resolution.

The use of these data was complicated by their reasonably comprehensive, although still incomplete, sampling of subcatchments: i.e. the data were sufficiently comprehensive to indicate with reasonable reliability the majority of those subcatchments in which each species occurs. They cannot be used, however, to indicate the relative abundance of species within occupied subcatchments, nor to indicate reliably the subcatchments from which species are absent; subcatchments may lack records for a particular species because the species is absent, because it is present but in numbers too low to be detected, or because it has been insufficiently sampled to detect a presence. Q7

To accommodate these shortcomings, the distribution records for each species were overlain onto the subcatchment layer and used to identify the planning units within which they had been recorded. For each non-migratory species, a single data point was created at the centre of the planning units containing one or more occurrences for that species. When calculating priorities, these point observations were loaded as ZONATION 'sites of special interest' points (SSIs; see Moilanen et al., 2012), together with the river, lake, and wetland ecosystem layers. During the prioritization process subcatchments were assessed not only for the relative contributions of the ecosystems that they contain, but also for the presence of any non-migratory species occurring within them.

The SSI points indicating subcatchments containing non-migratory fish species were initially included in the base prioritization with a weight of zero, allowing their representation to be assessed when ranks were calculated solely from the ecosystem layers. Further prioritizations were then calculated for which the weights for the SSI points were gradually increased through a sequence of 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, and 1.5. This allowed the balance between representation of ecosystems and species to be assessed over a range of weights, with a final weight chosen that provided for increased representation of non-migratory species while not excessively penalizing ecosystem representation.

2.6 | Adding migratory fish and ecosystem management units

Once a satisfactory balance had been achieved between the representation of ecosystems and of non-migratory fish species, further data layers were added describing the distributions of terrestrial sites (ecosystem management units, EMUs) receiving intensive management by the DOC, and of subcatchments selected by DOC freshwater staff as providing key habitat for migratory fish species (Appendix S2). The first of these data layers were selected for their ability to collectively represent a full range of terrestrial ecosystems, whereas the second were identified as providing the most favourable opportunities for managing healthy populations of migratory fish species. Input values for the EMUs consisted of a gridded layer in which cell values indicated the percentage of prescribed management actions that are currently implemented; values ranged between 0 and 100, with a mean of 39.6%. The locations of valuable sites for migratory fish species were identified by a binary (0/1) layer.

Weights for the EMU and migratory fish layers were varied following a similar process to that used for the non-migratory fish species. Their weights were initially set at zero to allow for an assessment of the representation of these sites when included in the prioritization analysis as passive players; their weights were then gradually increased while assessing the balance between the core freshwater ecosystems, non-migratory fish species, and the newly introduced EMUs and migratory fish sites, with final weights chosen to maintain a relatively even balance of representation across all features.

2.7 | Accounting for variation in statutory protection

A final prioritization was constructed to assess the representation provided by subcatchments that already have high levels of formal conservation protection, and to identify those with the greatest potential to complement these already protected sites. This was implemented by adding a layer identifying all third-order subcatchments in which 80% or more of the land area is protected either as public conservation land or by binding conservation covenants (Protected Areas Network – New Zealand, PAN-NZ). This layer was used to implement a hierarchical prioritization (Moilanen et al., 2012) in which 'protected' subcatchments, which comprise 25% of all subcatchments, were forced to occupy the highest prioritization positions (0–0.25), and all remaining subcatchments were ranked for their ability to complement the representation of a full range of freshwater ecosystems, as provided by the higher-ranked 'protected' catchments.

2.8 | River group protection and condition

Finally, two sets of summary statistics were calculated to further support the identification of river catchments where remedial actions might have maximum benefit. First, the average condition and the proportion of network length coinciding with statutorily protected land was calculated for each river ecosystem group. The results from this summary were combined with information describing the mix of ecosystem groups occurring within each third-order subcatchment to identify subcatchments containing a predominance of: (i) river ecosystems with low statutory protection; and/or (ii) river segments where their individual condition was significantly above that expected given the average condition nationally for the river ecosystems that they contain.

3 | RESULTS

3.1 | Updated river (catchment) pressure estimates

Implementation of the amended pressure formula across all New Zealand rivers and streams resulted in a significant improvement in discrimination between the most intensively farmed lowland sites (i.e. with high catchment clearance and high instream nitrogen concentrations, as in the lowlands of Waikato, Taranaki, Manawatu, Canterbury, and Southland) and catchments that have been extensively cleared of their natural cover, but for which instream nitrogen concentrations are generally lower because of the lower-intensity dry-stock farming that they support.

3.2 | Prioritizing river, lake, and wetland ecosystems alone

The top 25% of sites identified from the initial analysis using river, lake, and wetland layers alone, and applying longitudinal connectivity constraints, provided an average representation of 0.67 for both river and lake ecosystems and of 0.63 for wetland ecosystems. High-priority sites identified by this prioritization occur mostly in smaller catchments in coastal locations (Figure 2), with particular concentrations along the west coast of the South Island and on Stewart Island, i.e. locations with highly natural environments. Small coastal catchments with high priorities also occur in Southland, South Canterbury, the Marlborough Sounds, north Taranaki, eastern Bay of Plenty, around Auckland, and in Northland. Larger catchments with high priorities occur predominantly in the eastern South Island, and include the Clutha, Taieri, Waitaki, Ashburton, and Rakaia catchments; North Island counterparts are the Motu and Waihou catchments.

3.3 | Adding non-migratory fish distributions

Non-migratory fish species received relatively low levels of representation (~0.4) in the top 30% of sites when they were passive features in the prioritization analyses, i.e. with a weight of zero (left side of Figure 3). Their representation in the top 30% of sites increased to a level similar to that for the river ecosystems when they were given a weight of 0.1, with further increases beyond this as the weights were gradually increased, although the incremental gains in representation were lower once weights exceeded a value of around 1.0. Increasing the weights that were applied to the non-migratory fish observations also resulted in a gradual decrease in the representation of river ecosystems. Based on these results, a weight of 1.0 was identified as providing the most satisfactory balance between the representation of freshwater ecosystems and of non-migratory fish species. This resulted in relatively subtle changes in the geographic pattern of

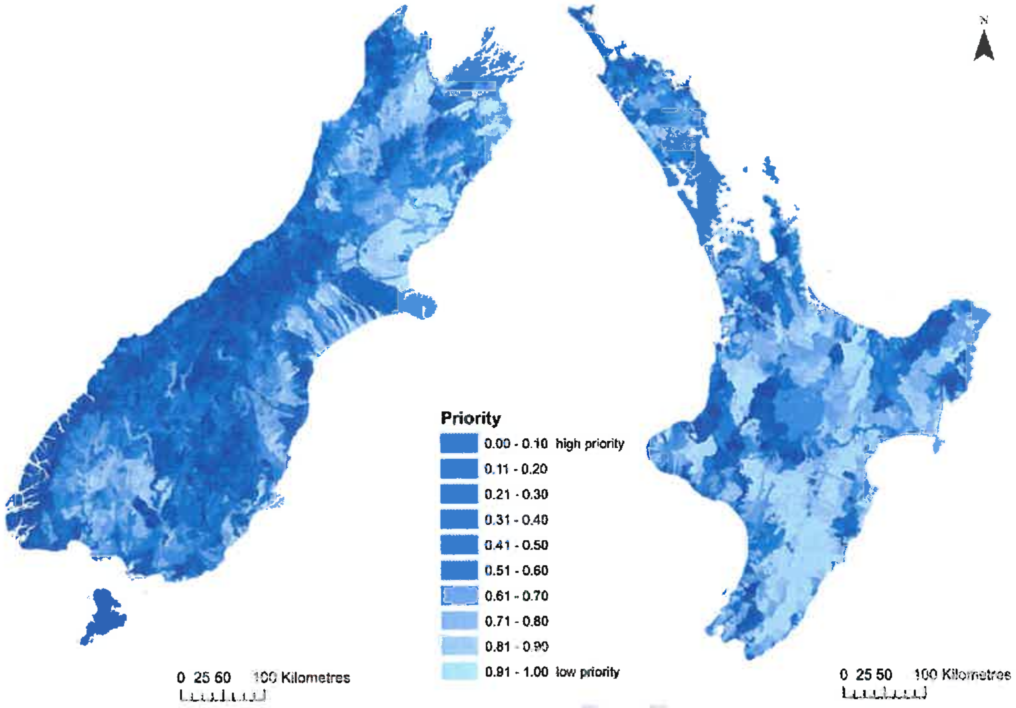

FIGURE 2 National priority of third-order subcatchments using river, lake, and wetland ecosystem layers, and applying longitudinal connectivity settings

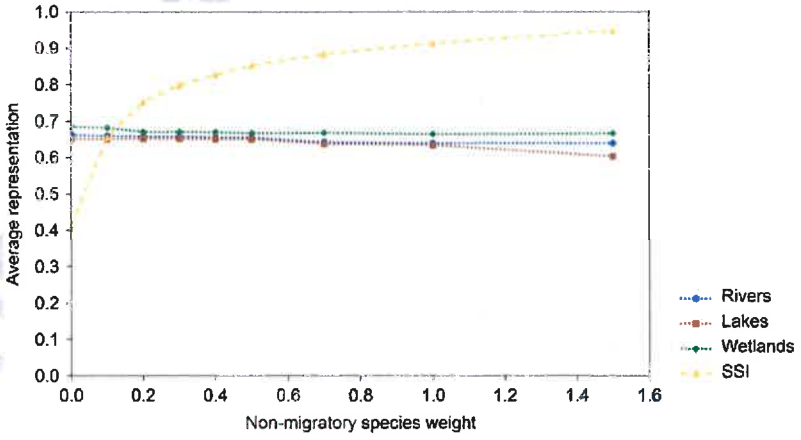

FIGURE 3 Changes in the average representation of river, lake, and wetland ecosystems, and point locations for non-migratory fish species in the top 30% of sites as a function of the weight allocated to non-migratory fish observations

high-ranked subcatchments, with a number of those that contain populations of non-migratory fish species, and particularly smaller river catchments, showing modest increases in priority (Appendix S3); by contrast, changes in priority in larger catchments containing non-migratory fish species were generally more muted (Figure 4).

3.4 | Adding migratory fish and ecosystem management unit sites

When migratory fish and terrestrial management unit polygons (EMUs) were added with zero weights, the EMUs received much greater representation in the top-ranked 30% of sites than migratory fish sites, reflecting the manner in which the EMUs were selected, i.e. to represent a full range of the terrestrial ecosystems of New Zealand. When positive weights were applied to these layers, however, the representation of the migratory fish sites increased much more rapidly than that for the EMUs. Subsequent analyses using respective weights for the migratory fish and EMU layers of 2 and 5, 5 and 10, 7.5 and 15, and 10 and 20, brought about a rapid increase in the representation of the migratory fish sites, but a more muted rise in the representation of EMUs (Figure 5). Weights of 7.5 for migratory fish sites and 15 for EMUs were selected as giving the most satisfactory overall balance (Appendix S4) between increased representation

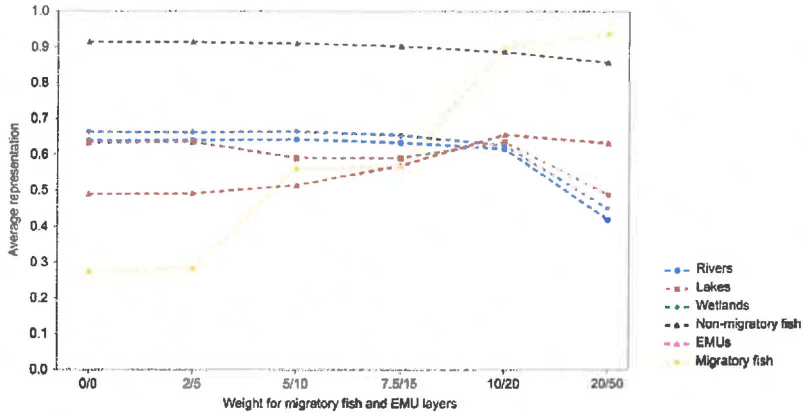

FIGURE 4 Changes in the average representation of river, lake, and wetland ecosystems, point locations for non-migratory fish species (SSIs), ecosystem management units (EMUs), and migratory fish sites in the top 30% of sites as a function of the weight allocated to the migratory fish and EMU layers

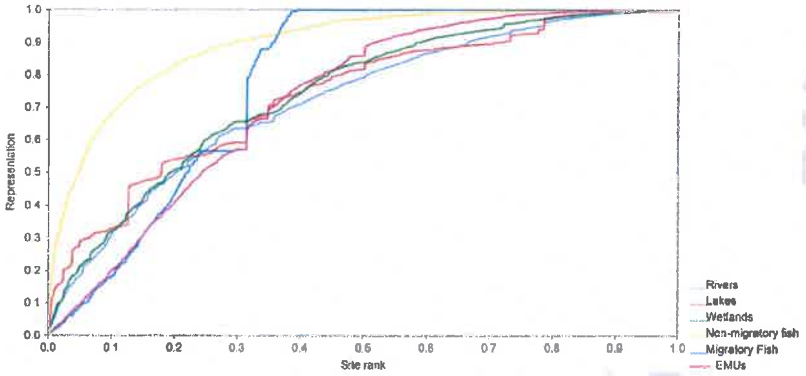

FIGURE 5 Representation of river, lake, and wetland ecosystems, point locations for non-migratory fish species (SSIs), ecosystem management units (EMUs), and migratory fish sites as a function of site rank. Site ranks indicate the proportion of sites to be included for protection or management, so that low values indicate high ranks

for these two new biodiversity features and maintenance of the representation of the freshwater ecosystems and non-migratory fish, as already included in the analysis.

National priorities identified by this analysis provide a balanced representation across river, lake, and wetland ecosystems, while also providing for representation of the additional features included in the analysis (Figure 6). Selecting the highest-ranked 25% of subcatchments from this analysis would deliver an average representation of 57, 56, and 60% for river, lake, and wetland ecosystems, respectively, whereas the EMUs and migratory fish sites would receive representation of 56 and 51%, respectively. Non-migratory fish species received the highest levels of representation in the top 25% of sites at 87%, reflecting the ability of ZONATION to identify sites that contain both these species (Appendix S3), and the distinctive river ecosystems in which many of them occur. Importantly, this high level of representation, which is consistent with their often critical conservation status, is achieved with only minimal reductions in the representation of other biodiversity features.

In spatial terms, patterns of high priority (Figure 6) are broadly similar to those from the initial prioritization analysis (Figure 2), but with some important differences. Larger catchments that show particular increases in priority include the Waitutu in Southland and the Motu in the Bay of Plenty, whereas the priorities of many small to middle-sized coastal catchments are adjusted to reflect the gains for fresh water likely to result from the broader management of EMUs, including the larger islands of Fiordland, around Okarito Lagoon, Punakaiki, Abel Tasman National Park, and on Kapiti and Little Barrier Islands; a number of other coastal catchments have increased priorities to reflect their importance for the maintenance of migratory fish populations.

3.5 | Accounting for legal protection

Results from the hierarchical prioritization, in which protected subcatchments were held back until all other subcatchments had been removed, clearly demonstrate the significant biases in the existing protected area network. This is evident in the graph of biodiversity representation as a function of rank, in which most features show a rapid rise in representation in the highest ranked subcatchments (progressing through the range 0–0.10, left side of Figure 5); by contrast, their representation rises more slowly with further progression to the right (0.10–0.25), with this plateauing effect reflecting the more limited selection options available within the 'protected' subcatchments that are forced to occupy the highest ranked positions (0–0.25). Representation then rises rapidly once non-protected subcatchments can be selected (ranks in the range 0.25–0.50), gradually approaching the levels of representation achieved by the non-constrained prioritization (Figure 6).

As a consequence of this behaviour, the top 25% of sites, i.e. those with 80% or more formal protection, provide much lower

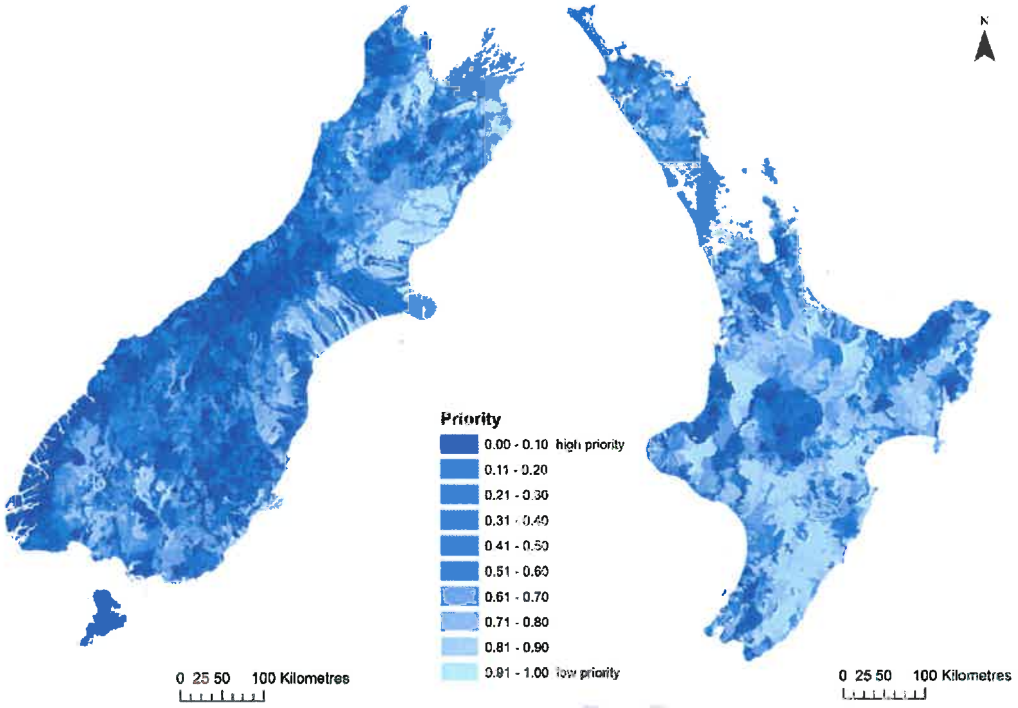

FIGURE 6 National priorities of third-order catchments from a prioritization combining layers describing the distributions of freshwater ecosystems, non-migratory and migratory fish, and terrestrial management sites (ecosystem management units, EMUs)

representation than the previous unconstrained prioritization for most biodiversity features (cf. Figure 7 versus Figure 6). The representation of rivers in the top 25% of subcatchments drops from 57 to 53%, the representation of lakes drops from 56 to 40%, the representation of wetlands drops from 60 to 42%, and the representation of migratory fish sites drops from 56 to 10%; the representation of non-migratory

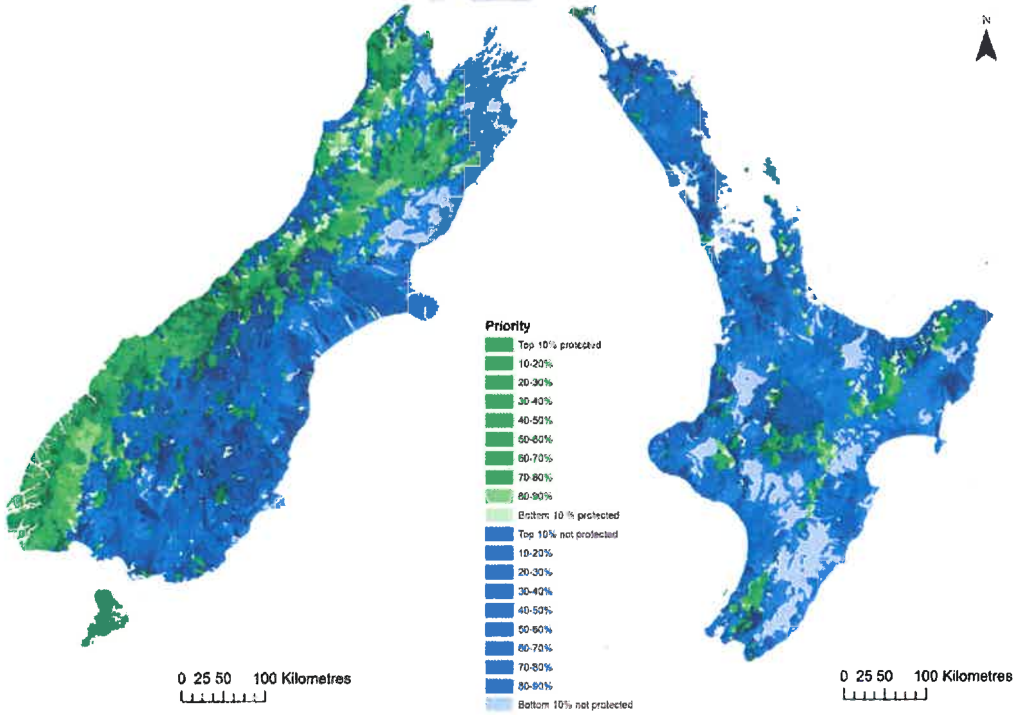

FIGURE 7 National priorities for third-order subcatchments from the protection-masked prioritization. Subcatchments with 80% of more of public conservation land or covenants occupy the highest ranks (0–0.25, green colours). Lower ranks (>0.25) indicate the ability of subcatchments with less protection to complement freshwater biodiversity values within existing protected sites

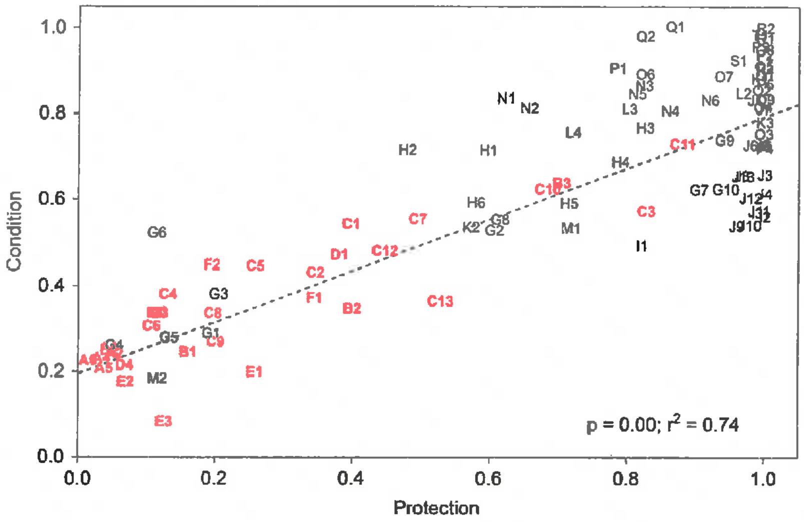

FIGURE 8 Relationship between the level of protection and the condition of 100 river groups. River groups in lowland areas are shown in red

fish species remains the same, whereas that for EMUs increases from 51 to 57%, reflecting the more frequent occurrence of both of these sets of features on sites with statutory protection.

The high priorities identified by this protection-constrained prioritization are located predominantly in environments that are less suited to economic development, in high-altitude and/or high-rainfall environments, particularly along the west coast of the South Island (Figure 7). Priorities in warm, and/or dry lowland environments are generally much lower, reflecting their generally very low levels of legal protection.

3.6 | River group protection and condition

Further evidence of the strong bias in representation of aquatic ecosystems by the existing protected area network is provided by the analysis of levels of protection and the average condition for individual river ecosystems. In particular, the 100-level groups (Leathwick et al., 2010) occurring predominantly in lowland environments (groups A–G, lower left side of Figure 8) not only have much lower levels of representation than river ecosystems occurring predominantly in colder, wetter environments (groups H–T, right side of Figure 8), but on average they are also in much poorer condition.

4 | DISCUSSION

The approach implemented in this analysis provides a powerful demonstration of the ability of spatial conservation prioritization analyses to guide freshwater conservation planning under a complex set of constraints, typical of those encountered by environmental decision makers. The task was to identify subsets of sites that would provide a balanced representation of a full range of biodiversity features (rivers, lakes, wetlands, non-migratory and migratory fish species), while also accounting for spatial variation in condition, longitudinal connectivity along river systems, existing terrestrial management, and biased patterns of legal protection. Building the prioritization analysis in a stage-wise fashion enabled us to progressively increase the complexity of the prioritization analysis, gradually building up to a full set of feature layers, with individual layer weights tuned using a transparent, evidence-based process to maintain an acceptable balance in representation.

Results from the prioritization using biodiversity features alone identified a set of subcatchments that most efficiently represent a full range of biodiversity features, while also exploiting the potential for overlaps with existing terrestrial conservation management programmes. It is particularly effective at identifying lowland subcatchments containing the best-condition examples of ecosystems that are generally in a degraded condition because of widespread land-use intensification. Strong arguments could be mounted, however, for this prioritization having a strongly aspirational nature, given its lack of consideration of the practical constraints imposed by different land tenures.

By contrast, the final protection-constrained prioritization demonstrates the significant shortcomings in representation provided by the existing protected areas network. It also identifies the locations outside this network that would most effectively increase the representation of a full range of aquatic ecosystems and species, while taking account of important functional linkages with protected subcatchments that can generally be expected to have retained good condition because of their existing protection. An important additional insight provided by this latter analysis concerns the differing status of protection for non-migratory and migratory fish species. In particular, the results indicated that non-migratory species are better catered for by the existing protected area network than are migratory species, i.e. they retain high representation in the top 25% of sites identified by the protection-constrained prioritization; by contrast, the significant drop in representation for migratory fish species from the biodiversity-alone prioritization to the protection-constrained prioritization highlights that the conservation of this group of species is heavily dependent on maintaining a set of subcatchments in good condition that are currently largely lacking formal conservation protection.

One significant scale-related challenge demonstrated by this analysis relates to the current wording of the DOC's freshwater goal, which emphasizes the restoration of rivers at the whole-catchment scale ('from the mountains to the sea'). In earlier trial analyses, prioritizations using entire catchments as planning units were calculated, but the results yielded much lower levels of representation, reflecting the homogenization of spatial patterns that occurs when patterns of occurrence are averaged across larger catchments. Further difficulties arose from the use of planning units that vary so markedly in size, and the relative paucity of larger catchments that have not suffered at least some significant degradation of habitat quality, generally in their lower reaches. By contrast, the use of third-order subcatchments as planning units, coupled with the specification of connectivity constraints, allowed for the identification of parts of larger catchments that retain a capability to contribute significantly to the representation of a full range of biodiversity, because at least some parts of them remain in good condition with sufficient upstream and downstream linkages to maintain broader-scale ecosystem functions. In light of this result, the use of subcatchment-scale prioritizations as the primary basis for identifying and planning freshwater management interventions is recommended.

Overall, the approach used here is congruent with similar, evidence-based planning in other jurisdictions, including those in Australia (Linke, Pressey, Bailey, & Norris, 2007), South Africa (Nel et al., 2011), and North America (Howard et al., 2018). The use of existing extents of protection and connectivity also enabled the identification of sites that provide the integrated protection (Abell, Lehner, Thieme, & Linke, 2017) required for effective catchment restoration and protection.

4.1 | Identifying sites for management

So far, these integrated catchment prioritizations have been used in a number of national and regional planning applications. They have been particularly well received in regional collaborative processes designed to identify high-priority biodiversity sites that are most likely to provide maximum gains in representing a full range of freshwater biodiversity features. Particular benefits have arisen from their ability to allow assessment of the value of locally proposed or favoured sites within a broader regional or national context, and to identify candidate sites that have not previously been considered by local staff or stakeholders. Using prioritizations in collaborative processes, the insights noted by Roux, Nel, Fisher, and Barendse (2016), such as opportunities for co-learning and refinements, were very apparent. The socio-ecological challenges and opportunities identified in Collier (2017) will also be better addressed by prioritizations, as used here, where freshwater values are not split into individual river, wetland, or lake ecosystems. Combining the results with estimates of average condition for the individual subcatchments, and the river groups that they contain, allows for the rapid identification of vulnerable subcatchments that are strong candidates for remedial action. This is most effectively achieved by focusing on high-priority, unprotected subcatchments that contain river ecosystems that have low levels of statutory protection nationally, and in which the average condition is higher than that expected for the ecosystems that they contain given their national average condition. The majority of the subcatchments prioritized using this approach have longitudinal connections with adjacent 'protected' subcatchments, making it easier to implement actions to protect or further enhance their status and provide catchment-wide benefits. By integrating river, wetland, and lake ecosystems, the prioritizations achieve a degree of cross-realm connectivity (Arthington, Finlayson, & Pittock, 2018; Leonard, Baldwin, & Hanks, 2017) by identifying the catchments that would add the most value to existing highly intact New Zealand freshwater ecosystems if restored and protected.

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