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Rainbow Springs). Luxuriant growths of watercress are often associated with springs (e.g. Waikoropupu Springs), and this plant is utilised throughout the country as a food source (Michaelis 1976b).

2.3 A SPATIAL DATABASE OF NEW ZEALAND SPRINGS

A key step in managing spring habitats is to identify and map their spatial distribution. Once the resource has been mapped, intrinsic values and potential anthropogenic threats can be identified. However, mapping all springs throughout the country is a huge task. We have made a significant start to mapping spring resources through searches of literature and New Zealand topographical data, and requests for information on the location of springs from NZ Freshwater Sciences Society listserver members and DOC conservancy staff. These searches resulted in the identification of 426 springs in New Zealand. In addition, Environment Canterbury (ECAN) maintains a spring database of over 1500 locations in their region. (www.ecan.govt.nz/EcanGIS/news.html, viewed May 2006). The locations of all identified springs are plotted on Fig. 4A (North Island) and 4B (South Island).

Each of the 426 springs located was assigned a reach number, based on the River Environment Classification (REC) (Snelder & Biggs 2002). This then allowed all springs to be linked to catchment characteristics, including geology, elevation, land use and climate. No ground-truthing was carried out to determine the validity of assignment of a given spring to a reach number, and this should be taken into account when interpreting the spring environmental summaries given below.

More than 50% of the springs were located at elevations < 400 m a.s.l. and were within 100 km of the coast (Fig. 5). This suggests that a large proportion of springs are located in lowland areas, where they are potentially most at risk from water quality deterioration and physical habitat modification associated with agricultural intensification. Taking the ECAN database into consideration further supports this conclusion (Fig. 4B).

In terms of geology, most springs (over 60%) were located in either alluvial or acidic volcanic areas[1] (Fig. 6A). This reflects the widespread coverage of these two geological classes, with volcanic rocks dominating the central North Island (Fig. 4A) and alluvium forming a major component of the South Island (Fig. 4B).

Land-use patterns indicate that more than 50% of springs are associated with stream reaches that fall under the pastoral land-use category of the REC (Fig. 6B). It should be noted that the REC reaches are classified as pastoral if the proportion of upstream pastoral land-use exceeds 25%. The REC does not provide information on local land use, which appears to be very important in determining the level of impact on springs (see section 4.4).

[1] Acidic volcanic is one of seven geology classes used to classify streams under the River Environment Classification (REC), see Snelder & Biggs (2002).

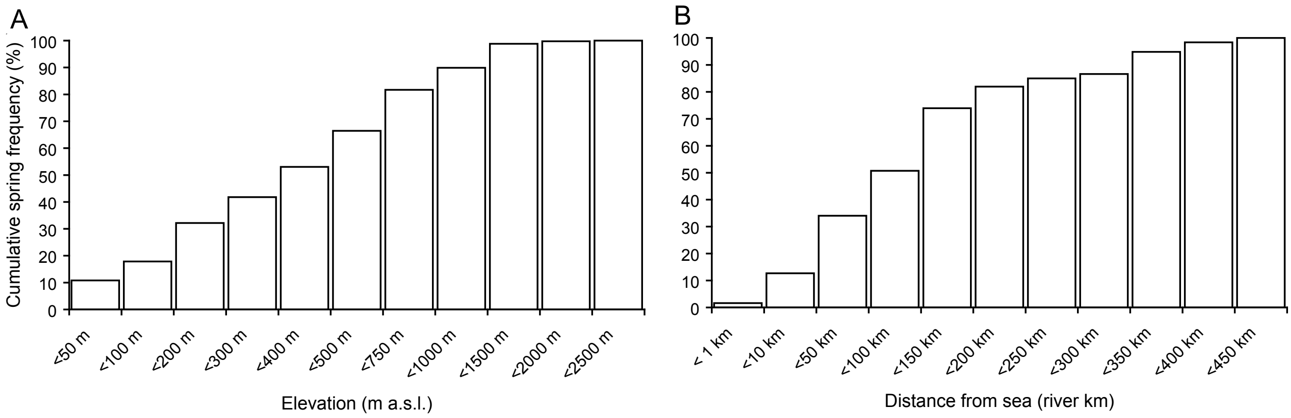


Figure 5. Frequency of 426 springs categorised by (A) elevation and (B) distance from the sea.

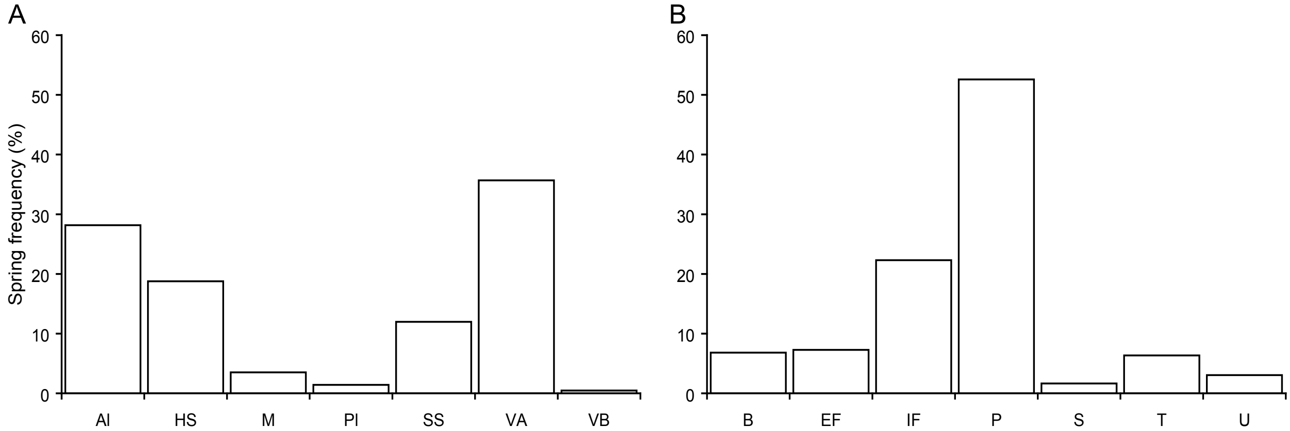


Figure 6. Frequency of 426 springs categorised by (A) geology and (B) land use. Key to REC geology codes: Al = alluvium, HS = hard sedimentary, M = miscellaneous, Pl = plutonics, SS = soft sedimentary, VA = volcanic acidic, VB = volcanic basic. Key to REC Land-use codes: B = bare ground, EF = exotic forest, IF = indigenous forest, P = pastoral, S = scrub, T = tussock, U = urban. These codes are explained in Snelder & Biggs (2002).

2.4 ALLUVIAL SPRINGS IN BRAIDED RIVER LANDSCAPES

Braided rivers occur throughout the world, most frequently in arctic and alpine regions with a distinct flood season, but they also occur in arid and Mediterranean climates subject to torrential rain, and in some tropical regions subject to monsoonal rains (Bravard & Gilvear 1996). The braided rivers of the South Island of New Zealand have been formed over the last 20 000 years as a result of glacial action, rainfall and snow melt (Gage 1977). The rivers are characterised by large, unpredictable floods, and by some of the highest sediment yields of the world's rivers (Winterbourn et al. 1981). For each river, these factors combine to produce an extensive, flat, alluvial flood plain across which the active channel of the river migrates back and forth. The active river channel is highly unstable, but is bounded by a mosaic of more stable elements, which can be classified according to their sedimentary deposits (Bravard & Gilvear 1996) or successional stage of the vegetation (Burrows 1977). Flood plains are recognised as being extremely patchy environments in terms of successional stage and habitat structure (Poole 2002). They also tend to have high hydraulic conductivity, allowing the formation of an alluvial aquifer and high levels of groundwater–

surface-water exchange (Woessner 2000). This shifting 3-dimensional mosaic provides a range of inter-connected aquatic habitat types within braided river landscapes.

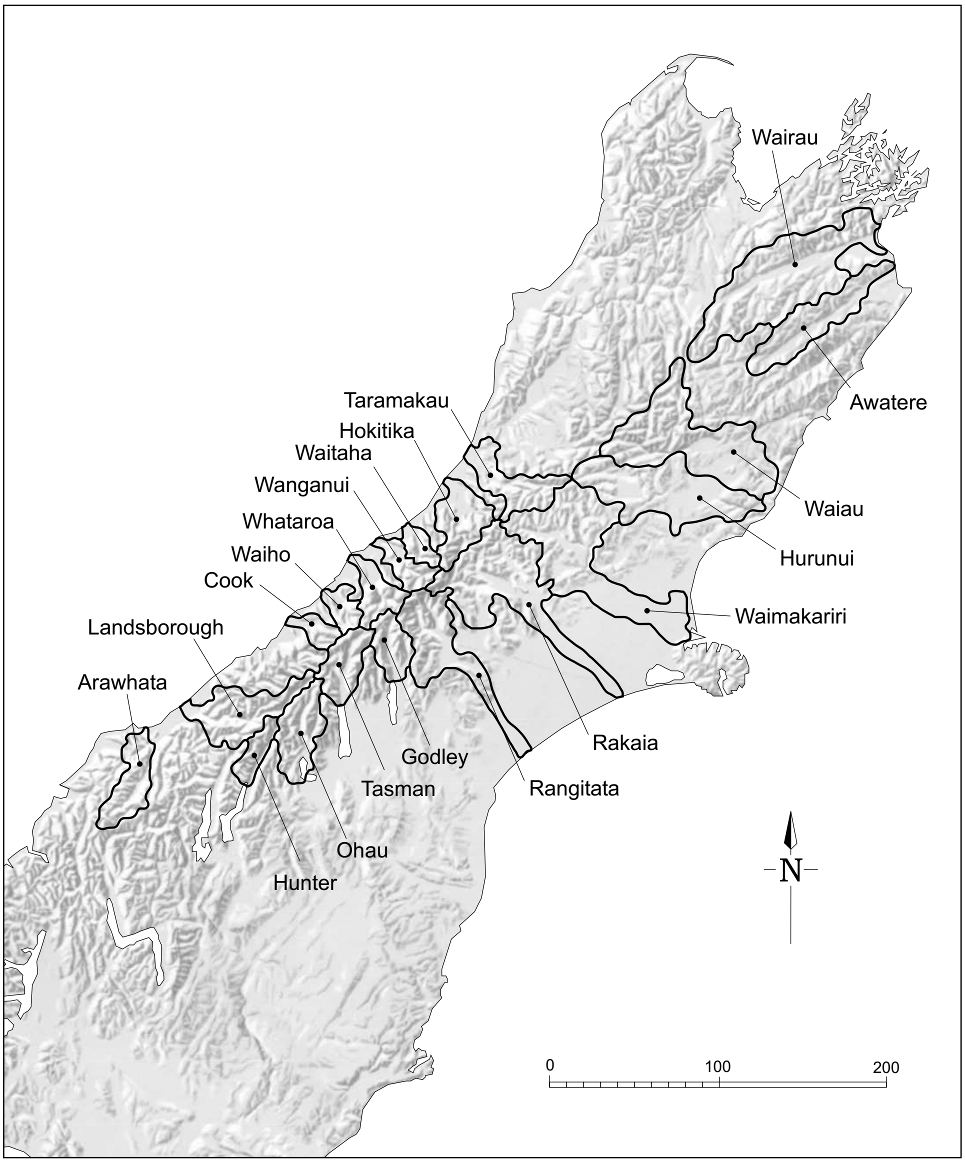
The location and relative age of springs in braided river landscapes are functions of the movement of water through the alluvium, which is determined by hydraulic pressure, depositional structure and the parent lithology of alluvial deposits (Stanford & Ward 1993; Valett et al. 1996; Woessner 2000). In general, the upper reaches of braided rivers are characterised by down-welling surface water, whereas the lower reaches exhibit up-welling. However, a flood-plain topography, valley constriction or the presence of impermeable layers within or beneath the aquifer can result in local patterns of aquifer recharge and discharge. This hydraulic connectivity results in a blurring of the perceived boundaries between the river and aquifer. Consequently, flood plains comprise a wide variety of aquatic habitats, many of which are linked by surface and sub-surface flow paths. Hydrological connectivity links a wide range of aquatic habitats, forming, in essence, a single body of water moving at variable speeds by multiple pathways through the flood-plain system.

The high connectivity generates flood-plain springs in areas of localised up-welling. These springs exhibit physico-chemical characteristics in complete contrast to those of the river main channel and constitute important habitats within the riverine landscape (Burgherr et al. 2002; Ward et al. 2002; Gray & Harding 2006).

Very little is known about the distribution and occurrence of braided river springs in New Zealand. However, Reinfelds & Nanson (1993) made an extensive investigation of stable flood-plain elements within the Waimakariri River catchment and found that the most extensive stable areas occurred in the upper river, in the lee of outcropping bedrock or alluvial tributary fans. These sites were characterised by late successional stage vegetation and numerous springbrooks, which flowed within the depressions formed by abandoned braid channels. Such streams, existing on stable, sheltered areas of flood plain, may remain undisturbed by river migrations for long periods of time. Reinfelds & Nanson (1993) suggested a period of 250 years might elapse before the entire Waimakariri River flood plain is re-worked.

Gray (2005) performed a mapping survey of springs within the braided reaches of 20 South Island braided rivers (Fig. 7). Springs were identified by eye from topographical maps (1:50 000 scale) as channels arising on the river flats with no surface link to a recognisable hill slope stream or no upstream connection to the main river. Spring permanence was indicated by the presence of vegetation and used to distinguish spring channels from backwaters and flood channels with an intermittent upstream connection to the main river. Springs were also classified according to the valley type within which they occurred (confined or flowing across plains), and according to any natural or human-made features with which they appeared to be associated, e.g. tributary fans, bluffs or flood retention works. A considerable number of springs occurred on vegetated islands within the main channel network of rivers, and were classified as being exposed to the destructive, eroding effects of the river.

Figure 7. South Island of New Zealand showing the 20 braided river systems analysed by Gray (2005). Catchments were delineated using the hydrological modeling tool within ARC GIS 8.2 (Environmental Systems Research Institute, Redlands, CA, USA) and the New Zealand 500 m Digital Elevation Model.



An important criterion driving the formation of braided reaches is slope. Braiding is found in valleys with gradients of 0.04–0.17°; an abundance of bed material; and a hydrological regime marked by major flood peaks (Bravard & Gilvear 1996). Interestingly, no springs were recorded in braided reaches with a gradient exceeding 0.9°. Possibly, the reaches exhibiting braiding with slopes above 0.9° and below the supposed braiding maximum slope of 1.7° are too unstable for the development of vegetated flood-plain elements and associated stable spring creeks.

Overall, Gray (2005) found that 65% of springs occurred within 0.5 km of a physical sheltering structure, such as a bluff, tributary alluvial fan or flood retention works, whereas the remaining 35% appeared to be exposed. Within four Canterbury rivers, alluvial fans and rocky bluffs were rare along the plains reaches. Exposed springs increased from approximately 20% of all springs in confined inter-montane reaches to being the predominant type on plains. However, in both valley types, the actual number of exposed springs was very similar. Consequently, the confined, inter-montane reaches of braided rivers contained the greatest number and diversity of springs by virtue of the presence of both exposed and sheltered sites.

16% of springs identified by Gray (2005) were within 0.5 km of flood retention works. This suggests that human activities can be constructive as well as destructive in terms of spring habitat and, therefore, biodiversity; but it also raises concerns about the extent of our knowledge of the long-term effects of activities such as gravel extraction and flood bank construction on the distribution of springs within braided rivers (see section 5.1).

Gray (2005) also undertook a comparison of spring types across catchments, and observed a correlation between mean reach slope and spring type. Rivers with a mean slope of less than 0.3° had a higher percentage of exposed springs than steeper rivers. Unfortunately, the pattern was blurred by the effects of flood retention works, particularly in the Taramakau and Wanganui Rivers on the west coast of the South Island. Despite this, the pattern suggests that stable, exposed flood-plain springs may be more common in lower-gradient rivers, or lower-gradient reaches of rivers. This relationship can also be seen in four Canterbury rivers, where the highest number of exposed springs are in the lower-gradient reach of the Rakaia River plains.

Although the exact mechanism of spring formation is not known, it seems likely that springs are a product of factors operating at multiple spatial and temporal scales. Porous alluvial flood plains characterised by high sediment loads and flood events are the result of glacial and fluvial action over thousands of years. At the local scale, up-welling and down-welling of water are regulated by the relative position of the flood-plain surface and the water table. Relative depressions in the flood-plain surface formed in the lee of large geomorphologic structures (i.e. fans and bluffs) result in up-welling at the point where the surface intersects the water table. In addition, the presence of impermeable barriers within the aquifer, or the constriction of the aquifer above a gorge, may produce positive hydraulic pressure and up-welling such that the water table rises to meet the surface of the flood plain. A final, but not mutually exclusive, possibility is that springs are fed by a shallow network of highly permeable preferential flowpaths embedded in a matrix of low-permeability substrate. Cut and fill riverbed erosion and zones of uniform deposition created these channels. Water flows rapidly along preferential flowpaths until the zone of high porosity intersects the surface, possibly within an abandoned braid channel, scoured lower than the surface of the surrounding flood plain.

It is highly likely that all these mechanisms are in operation simultaneously along the reaches of braided rivers and that different spring types show variable levels of permanence, stability and successional stage, resulting in a further increase in the habitat heterogeneity available across the flood plain. In terms of prediction, springs are likely to be more abundant in confined inter-montane valleys with complex geomorphology. Although springs appear to occur throughout braided river systems, the mechanisms and characteristics of the springs will alter with the morphology of the valley, thereby influencing the biological communities within the springs and the reach and landscape-scale contribution of these habitats to biodiversity.

3. Biodiversity values of New Zealand springs

3.1 HISTORICAL ECOLOGICAL STUDIES OF NEW ZEALAND FRESHWATER SPRINGS

The study of the biota of springs (crenobiology) is well established overseas (see reviews in Ferrington (1995) and Botosaneanu (1998)). In contrast, there have been few studies on the ecology of New Zealand's coldwater spring habitats. The first studies describing the biological communities inhabiting New Zealand freshwater springs were of Western Springs, Auckland (Johnstone 1972); Avon River/Otakaro, Christchurch (Marshall 1973); and Waikoropupu Springs and five other coldwater springs elsewhere in New Zealand (Michaelis 1974, 1976a, b, 1977). At the end of the 1970s, Russell & Rodgers (1977) characterised the waters of Western Springs and Cowie & Winterbourn (1979) investigated the biota at the spring source of Middle Bush Stream, an alpine springbrook near Cass, central South Island. During the next 20 years, there were no studies characterising biological communities or spring habitats, although the origin of some springs of the east coast of the North Island was studied (Hunt & Glover 1995) and some ecological studies compared springbrook biota with invertebrate communities of unstable streams fed by run-off (e.g. Death & Winterbourn 1994; Death 1995) or included them as sites in experimental work (Rounick & Winterbourn 1983; Rounick & James 1984; Winterbourn & Fegley 1989; Suren 1991).

In the last 5–10 years there has been a marked increase in interest in New Zealand freshwater springs, with a variety of topics being addressed. For example, studies have been undertaken on the ecology of Spring Creek (Young et al. 1999) and of other spring-fed streams on the Wairau River plain, Marlborough (Young et al. 2002), the effects of land use on freshwater springs (Scarsbrook & Haase 2003), and the spatial and longitudinal patterns of invertebrate communities in springs (Barquín 2004). A chapter in the book 'Freshwaters of New Zealand' (Death et al. 2004) draws together what is known about both coldwater and geothermal springs. An identification guide to bryophytes and algae of Waikoropupu Springs has also been published (Fife et al. 2004), and several spring studies have been published recently (Barquín & Death 2006; Collier & Smith 2006).

In the only published biodiversity survey of coldwater springs to date in New Zealand, Michaelis (1976a, 1977) focused on Waikoropupu Springs, but also sampled five other coldwater springs in the North and South Islands. Michaelis (1977) found 16 species of algae, seven species of moss, three species of liverworts, five angiosperms and 40 species of aquatic invertebrates. The snail *Potamopyrgus antipodarum* was found at all six cold springs sampled, and made up 88%–96% of total invertebrates at Waikoropupu Springs.

Springs also contribute to functional diversity of ecosystems. For example, Digby (1999) found that levels of secondary production in spring habitats in the Rakaia River were an order of magnitude higher than in the main

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