WATER REGULATION

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ABSTRACT: Water flows in rivers are regulated by a number of natural and human factors that result in the flow regime of a river. Several indices of flow regime are identified: these are the mean annual flood, the number of floods above a threshold (FRE3), the mean flow, the sequence of mean monthly flows through the year, and the mean annual 7-day low flow. These are useful indices that together help describe a flow regime. Values of FRE3 vary from 0 for spring-fed streams to over 20 for some West Coast streams. Specific mean flows, reflecting annual rainfall, vary from about 280 L s^{-1} km^{-2} for South Island West Coast rivers to less than 7 L s^{-1} km^{-2} for small east coast rivers. Specific mean annual flood flows, which are influenced by rainfall intensity, catchment storage (lakes, lithology) and catchment area, vary from over 5000 L s^{-1} km^{-2} to less than 60 L s^{-1} km^{-2}. Seven-day minimum flows with return periods of 2 years, determined primarily by rainfall regime and catchment storage, range from over 50 L s^{-1} km^{-2} to less than 1 L s^{-1} km^{-2}. The factors regulating water flows are explored: they are principally climate (precipitation and evapotranspiration), geology, vegetation cover, and human activity. The importance of the flow regime to river biota and to human use of water is examined.

Key words: base flow, ENSO, flow duration curve, flow regime, flow variability, FRE3, hydrograph, instream habitat, IPO, land use change, quick flow, rainfall.

INTRODUCTION

Water flows in rivers are regulated by a number of natural and human factors. At the highest level there is the climate, where water flows are regulated by the balance between precipitation and evapotranspiration. The magnitude and timing of flows depends on the season when rainfalls occur and the nature of the precipitation-whether it is snow or rain. The magnitude and timing is also influenced by geology, land cover, the presence of lakes, and by humans. Humans manipulate rivers with dams for hydropower generation and irrigation and abstraction of water for run-of-river irrigation or municipal supply.

In New Zealand a wide range of river types reflect the parameters regulating the river: boulder-filled mountain torrents, issuing from glaciers in mountains only a few kilometres from the coast; wide, braided, gravel-bedded channels; meandering silt watercourses; and tree-lined urban waterways. Some rivers that rise in the high mountains may change dramatically along their course, before discharging via a lagoon or estuary to the sea. Rivers rising in the foothills or from lowland springs tend to have more uniform morphology.

But every river has its own unique character. What makes each one different? The answer lies in the combination of physical and climatic features and human influences that regulate the flows and influence what we call the "flow regime" or "hydrologic regime" of a river.

WHAT IS FLOW REGIME?

The flow regime (or hydrologic regime) of a river is the unique way that its flow changes from day to day, season to season, and from one year to another. Regime defines the character of a river, how liable it is to flood or to experience long periods of low flow, what it looks like, what lives in it, whether it is potentially useful. For particular management purposes, various aspects of flow regime may be significant, but in general we require information about extreme high flows, extreme low flows, average flows (equivalent to the total volume of water discharged by the river), flow variability, and the frequency or spacing of significant events, such as "flushing flows".

A hydrograph is a graph of the change in either a river's water level (often called stage) or its flow (discharge in m^3 s^{-1}) over time. Two main components of river flow can be identified from a hydrograph: base flow and flood flows (often termed quick flow) (Figure 1). The base flow of a river is derived from seepage of ground water into the channel or from spring or lake outflows; it may be large or small, but it tends to change slowly. Flood flows occur on top of the base flow. They are produced from precipitation directly into the channel, from overland flow down surfaces sloping into the channel, from water that infiltrates into the soil and moves quickly to the stream channel (interflow), and from runoff from wet areas near stream channels. Flow regimes differ in the magnitude and frequency of high and low flows due to differences in total precipitation, as well as in their flow variability, the magnitude of high and low flows relative to base flow, and their flashiness (Snelder and Biggs 2002). Differences in flow regime are best illustrated by looking at graphs of flow from different rivers (Figure 2).

The flow duration curve (FDC) is another way to describe differences in flow regimes between rivers. The FDC represents the relationship between magnitude and frequency of flow by defining the proportion of time for which any discharge is equalled

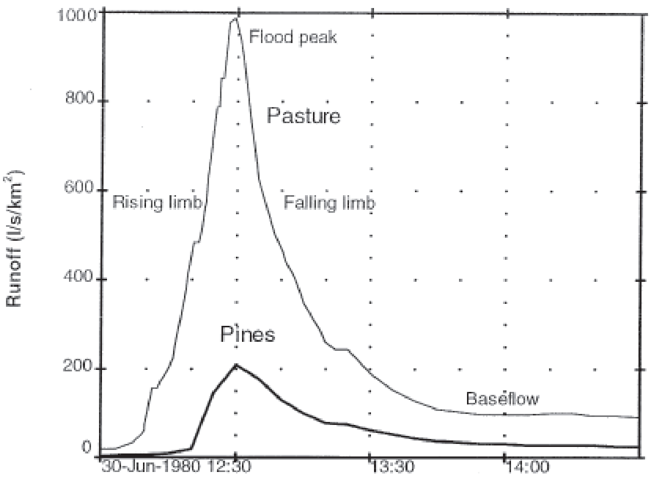

FIGURE 1 The key components of a hydrograph. The difference in regime caused by change in land use is shown by hydrographs from a pasture catchment (thin line) and a pine catchment (thick line) of similar size (approximately 7 hectares) for the same rainstorm.

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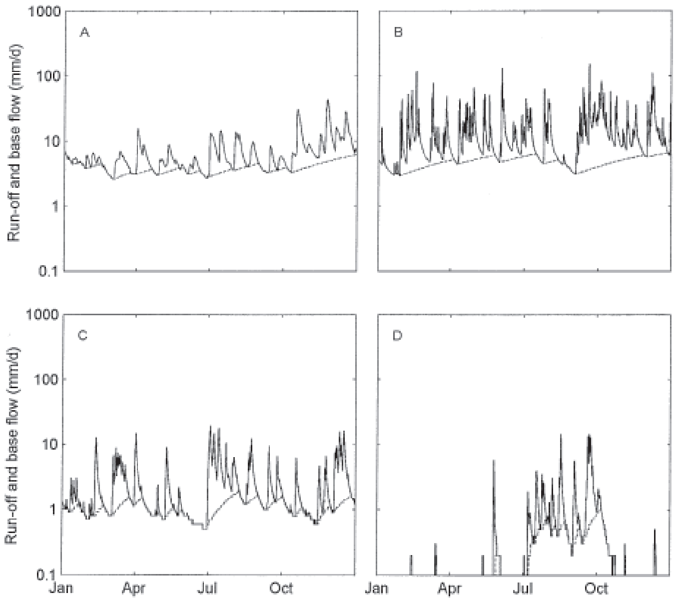

FIGURE 2 Examples of annual runoff and base flow hydrographs of rivers with low- and high- variability flow regimes. Note the logarithmic scale. The dotted line separates base-flows from flood flows using the method of Hewlett and Hibbert (1967). A is Buller River (Westland) (195 km^2, FRE3=4.6). B is Ahaura River (Westland) (790 km^2, FRE3=17.5). C is Wairoa River (Tasman) (464 km^2, FRE3=19.9). D is Whareama River (Wairarapa) (398 km^2, FRE3=0.7).

or exceeded (Vogel and Fennessey 1994). FDCs are useful graphical tools for evaluating flow variability at a particular site that can be used for water resources assessments, including power supply schemes, reliability of water supply, water quality assessments and the evaluation of river habitats (Booker and Snelder 2012). Figure 3 shows normalised FDCs for the rivers shown in Figure 2. Normalising was achieved by dividing the flow of a site by the mean flow of a site. This is necessary when comparing FDCs for different rivers with very different mean flows. The relatively small floods and sustained flows from the Buller River at Lake Rotoiti are shown by the large proportion of the time that the flows are close to the mean flow. The other extreme is the Whareama River where a much larger proportion of the time the flows are either very high or very low.

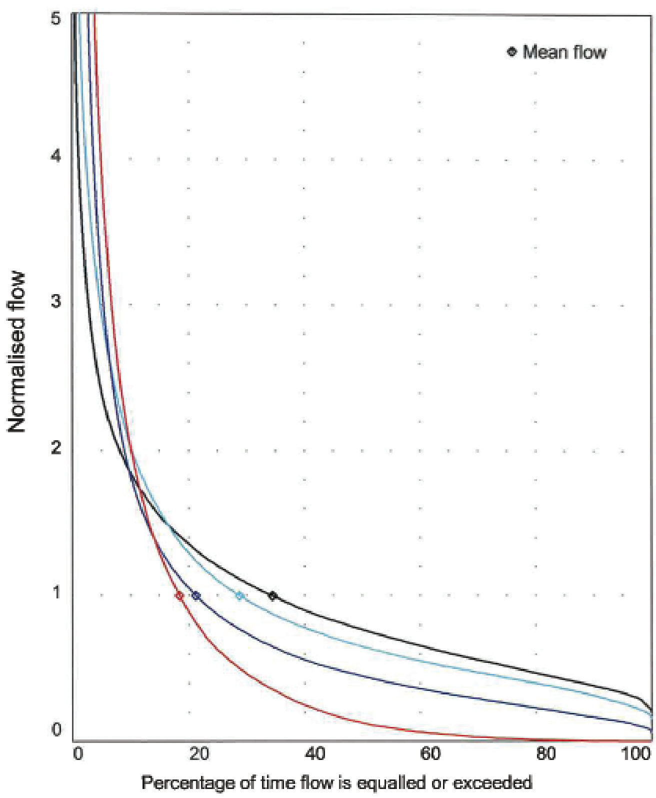

FIGURE 3 Examples of flow duration curves for 1971–1991 for the rivers shown in Figure 2. Black line Buller River at Lake Rotoiti, light blue line Ahaura River, blue line Wairoa River, red line Whareama River. (diamond symbol indicates the mean flow).

Hydrographs of floods commonly show the rise of floodwaters (termed the "rising-limb") and their recession ("falling-limb") (Figure 1). The slopes of the rising and falling limbs tell us about the nature of the rainfall that caused the flood and also about the catchment itself. For example, during "flash floods" caused by intense rain falling onto an already saturated catchment, streams rise rapidly because a greater proportion of the water runs directly into the stream network rather than soaking into the ground.

In hydrograph analysis, base flow and flood flow can be separated by drawing a line from the start of the rising limb of a flood to a point on the falling limb. Because the base flow is usually higher after a flood, the line has an upward slope that is usually selected based on experience – a figure of 0.004 (mL s^{-1} km^{-2}) s^{-1} (Hewlett and Hibbert 1967) was used to separate base flows and flood flows in Figure 2.

The particular combination of base flows and flood flows for a river is a crucial aspect of its flow regime. Rivers may have a stable regime with a limited variation in flow, or a regime with very variable flows. The Buller River at the outlet of Lake Rotoiti (Figure 2A) shows small, regular, slowly rising and falling floods throughout the year, on top of a large sustained base flow. The opposite extreme is illustrated by the Whareama River (Figure 2D), which shows a clear seasonal pattern of virtually zero flow in summer but a sustained base flow in winter, with frequent, short, flashy floods. Floods may happen regularly, e.g. virtually weekly on the South Island's West Coast, or only occasionally. In some rivers, floods are seasonal – often in winter and spring in east coast streams.

WHY IS THE FLOW REGIME IMPORTANT?

The river as a habitat

The flow regime of a river, in combination with other factors such as temperature and water quality, influences the plants and animals that can live in it. As an example, consider the conditions favourable for brown trout. They like cool, clear, bouldery rivers that have stable flow regimes with few floods and high base flows. There are several reasons for this. When the riverbed is nearly always covered in water the food chain can maintain full production. Algal slimes can grow on the gravels and boulders on the riverbed, and aquatic insects, the main food of trout, in turn can feed on the slimes. If there are frequent floods, slimes (Biggs 1990) and insects (Sagar 1986; Scrimgeour et al. 1988; Jowett and Richardson 1989; Quinn and Hickey 1990b) get ground off or washed away as the riverbed moves in the flood, and there is less food for both insects and trout. Streams with high base flows almost always have water deep enough for trout to hide and rest. Another favourable condition relates to spawning. In a stable flow regime, it is less likely that floods will wash away the redds (areas where the eggs are laid), and there will usually be enough water to carry oxygen through the gravels to the eggs. The clear water preferred by trout has little sediment to clog up redds and enables them to see prey drifting in the water column.

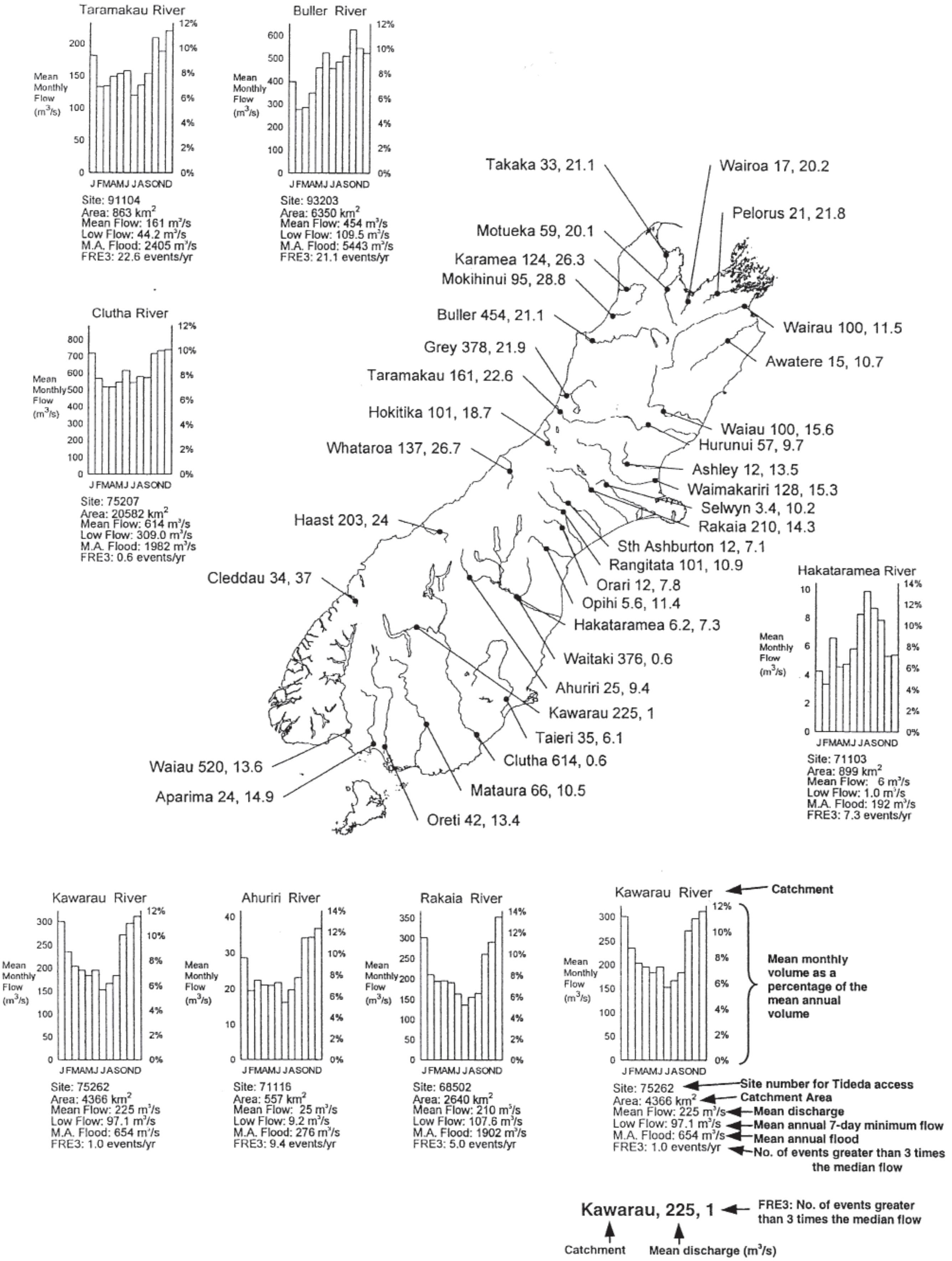

FIGURE 4 Indices of flow regime for representative catchments, South Island (Source: National Institute of Water and Atmospheric Research and Regional Council archives).

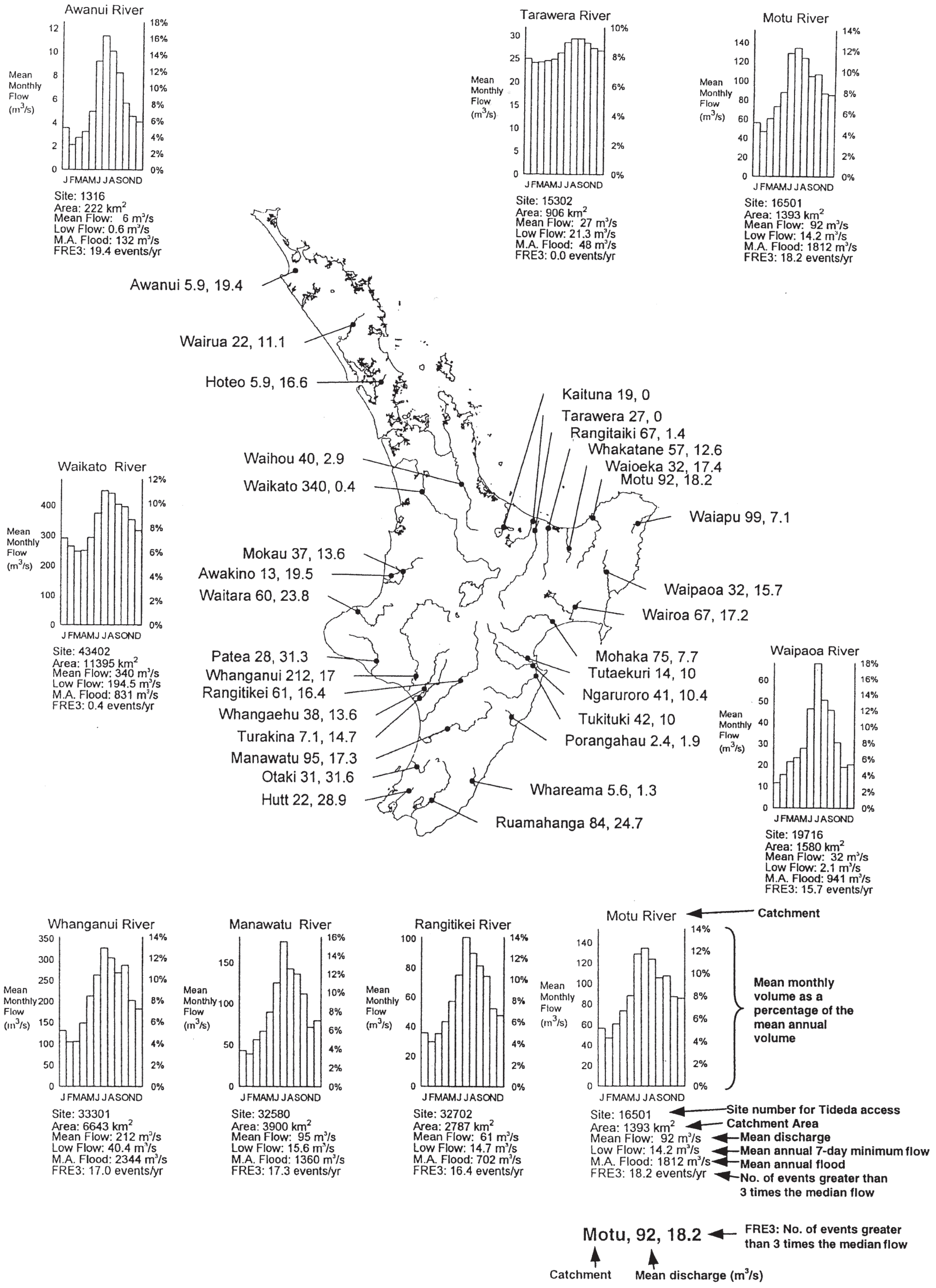

FIGURE 5 Indices of flow regime for representative catchments, North Island (Source: National Institute of Water and Atmospheric Research and Regional Council archives).

Boulders provide both white water to hide, and still areas to rest. Thus, trout are adapted to survive in a stable regime. However, other creatures may prefer conditions associated with other types of flow regime (Sagar 1986; Scrimgeour et al. 1988; Biggs 1990; Quinn and Hickey 1990a, b).

Human use of rivers

A river's flow regime also affects the way in which people can use it. For example, monthly flows in rivers like the Rakaia and Ahuriri Rivers (Figure 4), which drain from the Southern Alps, are highest in spring and summer. This is also the time of highest demand for irrigation waters. Therefore, water can be taken directly from the river on a "run-of-river" basis, and there is less need for costly storage reservoirs. On the other hand, demand for hydroelectric power in New Zealand currently peaks in mid-winter, and control structures have been built to augment and manage the storage capacity of lakes such as Tekapo, Pukaki and Hawea, which have river inflow patterns with a winter minimum, similar to those of the Rakaia and Ahuriri (Figure 4).

Sometimes a river's flow regime is very suitable for one use but poor for another. For example, Nelson rivers have a monthly flow regime similar to that of the Hakataramea River in South Canterbury (Figure 4), in which summer flows are low, with slow clear water. These conditions are ideal for swimming, and suit holidaymakers visiting Nelson. On the other hand, this same flow regime restricts the amount of water available to irrigate Nelson's important horticultural crops.

INDICES OF FLOW REGIME

What methods are used to describe and compare various aspects of the flow regime of a river? Flow regimes can be discussed in terms of the variation of the flows, for example, the frequency of floods above a given threshold, the sequence of mean monthly flows through the year, or the mean annual 7-day low flow. Each of these tells us something different about the flow regime of a river. Indices of flow are often expressed in terms of specific discharge (flow per unit area, in L s^{-1} km^{-2}), to help in comparing catchments of different sizes.

Maps and information on mean flows, sediment discharges, river temperatures, low flows, and floods of New Zealand rivers can be found in Duncan (1987) and in Figures 4 and 5. Other studies usually concentrate on single aspects of the flow regime, such as low flows (Hutchinson 1990) or floods (McKerchar and Pearson 1989).

The River Environment Classification (Snelder and Biggs 2002) used 13 different variables to characterise the intra-annual variation in flow conditions relevant to five ecologically significant aspects of flow regime suggested by Richter et al. (1996), Poff et al. (1997), and Poff and Ward (1989): magnitude of the flow variation, frequency of flows above a threshold, duration of high and low flows, timing of flows and rate of change of flows. One useful and ecologically significant measure of the frequency of high flows is the average number of floods per year (based on the mean daily flow) exceeding three times the median flow-(FRE3) (Clausen and Biggs 1997, 1998).

Variation of flows

The value of FRE3 unlike other measures of flow variability such as the coefficient of variation (CV) of flow (the standard deviation of flow divided by the mean flow), has been shown to be ecologically relevant (Clausen and Biggs 1997, 1998). It provides a simple index of the flow variability that in part determines the ability of algae, macro-invertebrates and other aquatic biota to become established. From measurements of periphyton biomass in 26 New Zealand rivers, Clausen and Biggs (1998) showed that as FRE3 increased, the amount of biomass decreased. The same study examined the relationship between FRE3 and benthic invertebrate numbers for 63 sites, and found a slightly curvilinear relationship with high densities for intermediate values of FRE3 (10–20 freshes per year). The rivers used to develop FRE3 were relatively small single thread rivers (Clausen and Biggs 1997) with relatively benign hydrological regimes. For large steep rivers with relatively harsher flow regimes, such as the large braided rivers of Canterbury, FRE2 (the average number of floods per year exceeding two times the median flow) may be a better index of disturbance.

FRE3 must be considered as an indicator of flood events that cause ecological disturbance, rather than as a threshold. Successively higher flows cause increasingly high shear stresses over increasingly large areas of the riverbed, so sediment movement and sloughing of algal mats become increasingly frequent and widespread. Although a threshold of motion for sediment transport can be defined for a given sediment type, it is more difficult to identify a "threshold of ecological disturbance" – indeed, algal mats can slough off even at low flows, if the mats become large enough. A given "FRE3 flood" (one that peaks above three times the median flow) is not necessarily more ecologically significant than a smaller fresh; factors such as the preceding sequence of flows must also be considered – FRE3 floods occurring within a few days of one another will have an effect similar to a single flood as the periphyton and invertebrate populations would not have had enough time to recover.

A low FRE3 value indicates a stable flow regime. Rivers with few floods (FRE3 <5 per year) tend to be mainly spring-fed or controlled by lakes, such as the Buller River at Lake Rotoiti (Figure 2A). Their flow is mainly base flow, and floods are usually small. Such rivers are typically rich in nutrients and they normally support a large amount of stream life. Rivers with much more variable flow (FRE3 >10 per year) tend to drain high rainfall areas: they have a high base flow, but also have frequent, large floods that disturb the riverbed. These conditions do not allow aquatic plant and animal communities to develop fully (Biggs et al. 1990). West Coast rivers such as the Ahaura (Figure 2B) fall into this category. Some rivers have long periods of low flow, low base flows, large infrequent floods of short duration, and very low FRE3 values, for example, the Whareama River (FRE3 <1 per year) (Figure 2D). Periphyton growth can rise to nuisance levels, and midges, snails and worms dominate the invertebrate fauna in such rivers.

Figures 4 and 5 show the mean flows and FRE3 of 67 of the country's larger or more economically important rivers. Some large South Island West Coast rivers and large east coast rivers such as the Clarence River in Marlborough are not included because their flows have not been reliably measured. The mean flows shown are the natural river flows, the flows that would be expected if there were no man-made diversion of flow from one catchment to another.

Values of FRE3 may be required for rivers without a flow record. Booker (in press) has developed a method for predicting FRE3 for 500 000 river reaches describing New Zealand rivers using a number of rainfall parameters, catchment elevation and area, average slope and river particle size.

Monthly flow histograms

Month-to-month variations in river flow (Figures 4 and 5) primarily reflect the seasonal distribution of rainfall and snowfall in New Zealand. The winter rainfall peaks in the north are reflected in the flows of the Awanui, Motu, Whanganui and Manawatu Rivers, while the more even distribution of rainfall in central New Zealand is illustrated by the flow of the Buller River.

The monthly flows of the Rakaia, Kawarau, and Ahuriri Rivers are characteristic of alpine snow-fed rivers, where winter precipitation is held in the snow pack and released in the spring and summer thaw. However, the high spring and summer flows are also a response to rainfall from the northwest winds that prevail then. The flow pattern of the Taramakau River, typical of the many short, steep and large rivers draining the Southern Alps to the west, shows the same traits but is less influenced by snowmelt.

In the Volcanic Plateau of the central North Island, rainfall percolates through the fractured pumice into the groundwater system and is released evenly by spring-fed streams, as in the Tarawera River (Figure 5). Many of the rivers with headwaters in the central North Island show some influences of their pumice cover. A comparison of the Waipaoa River, which drains Tertiary sedimentary rocks, with the Rangitikei or Whanganui River shows how much the flows are moderated in the latter rivers.

Lake storage and the even release of water for hydroelectric power generation are responsible for the uniform monthly flow of the Clutha at Clyde (Figure 4). Its monthly flows vary much less than those of its tributary the Kawarau, even though Kawarau monthly flows are somewhat moderated by uncontrolled storage in Lake Wakatipu. The Buller River also shows the smoothing influence of Lakes Rotoiti and Rotorua on its monthly flow fluctuations.

The Hakataramea River is typical of foothills-fed east coast rivers, with high flows in late winter and spring, and low flows in summer and autumn. These reflect the generally low east coast rainfall, and dry summers when the soil dries out (Figure 4). Only when soil moisture is fully replenished by a combination of winter rainfall and low rates of evapotranspiration is there sufficient rainfall to increase flow substantially.

Specific discharge

Specific discharge (also known as specific yield) is the flow per unit of catchment area, usually expressed in litres per second per square kilometre (L s^{-1} km^{-2}). It allows the flows from catchments of different sizes to be directly compared. It can also be converted to depth of runoff in millimetres per year, and is therefore more easily compared with rainfall. Further insights into a river's regime may be made by examining its specific discharge for various parts of its flow, such as low flow, mean flow or flood flow.

The mean specific discharge strongly reflects catchment rainfall and evapotranspiration. Figures 4 and 5 show data for the major rivers of New Zealand, and flow rates for 95 smaller river sites can be found in Close and Davies-Colley (1990). The range for the North Island rivers shown in Figure 5 is 8–101 L s^{-1} km^{-2} (290 mm yr^{-1} to 3190 mm yr^{-1}) for the Porangahau and Otaki Rivers respectively. However, most of the catchments yield about 34 L s^{-1} km^{-2} (1070 mm yr^{-1}) reflecting the relatively even distribution of rainfall over the North Island. The range for South Island sites is much wider, with the Whataroa River yielding a high 310 L s^{-1} km^{-2} (9840 mm yr^{-1}) and the Hakataramea River only 6.7 L s^{-1} km^{-2} (210 mm yr^{-1}). The Whataroa catchment runoff of nearly 10 metres yr^{-1} is by no means uncommon, as the Hokitika at Colliers Creek (catchment area 352 km^{-2}) yields 8700 mm yr^{-1} of runoff. To this, estimated evapotranspiration of 600–700 mm yr^{-1} must be added (Finkelstein 1961), indicating an annual rainfall of about 9500 mm over the whole catchment.

Specific mean annual flood flows (that is, the average of the annual peak flows, per unit catchment area) reflect storm rainfall intensities, which normally increase with annual rainfall. However, the highest rates for the North Island (Figure 5) are for rivers towards the north, which are subject to storms originating from tropical cyclones. These include rivers such as the Awanui, Motu and Waipaoa, which have specific mean annual floods of 630, 1140 and 690 L s^{-1} km^{-2} respectively. Many of the other North Island rivers have specific mean annual floods of about 300 L s^{-1} km^{-2}. The Waikato and Tarawera Rivers have very low specific mean annual floods of 60–70 L s^{-1} km^{-2}, because lake and ground water storage in the pumice of the central volcanic plateau have a strong damping effect on their flood regimes. The annual maximum floods and related statistics for 343 rivers nationwide can be found in McKerchar and Pearson (1989).

Low flows are determined by the recency of rainfall, catchment groundwater storage and its rate of outflow (a function of the underlying rocks and lakes), and catchment area. The lowest flow per unit area during a period of 7 consecutive days that could be expected to occur on average every 2 years is called the 7-day mean annual low flow. It is a particularly important index for management of instream flows because it represents the extreme low flows that are likely to limit the life-supporting capacity of a waterway. Such flows vary from about 500 L s^{-1} km^{-2} in the Taramakau River to as little as 1 L s^{-1} km^{-2} in the Hakataramea River; they are primarily a function of annual rainfall and geology. Catchments with small low flows also tend to have long periods with low flows. Hutchinson (1990) lists low flow magnitude and frequency from 428 sites nationwide.

FACTORS REGULATING RIVER FLOW REGIMES

The factors regulating water flows are principally climate (precipitation and evapotranspiration), geology, vegetation cover, and human activity such as flow diversion for hydroelectricity generation or irrigation.

Climatic influences

Rainfall and evapotranspiration distribution — The major climatic factors influencing water regulation are how often and how hard it rains, and how rapidly moisture is returned directly to the atmosphere by evapotranspiration. Examination of the annual pattern of rainfall and evapotranspiration goes a long way towards explaining why a particular river has a particular flow regime.

New Zealand's rainfall pattern results from its long narrow shape, steep topography, and isolated island position. The country's mountain backbone lies directly across the path of the eastward-moving anticyclones and low-pressure troughs that are characteristics of the "Roaring Forties". The passage of these weather systems results in a high and regular rainfall over much of the country, although some places get much more rain, more often, than others. Mean annual rainfall varies from as little as 300 mm yr^{-1} in a small area of Central Otago to over 10 000 mm yr^{-1} in a long narrow strip to the west of the crest of the Southern Alps (Griffiths and McSaveney 1983; Henderson and Thompson 1999). An annual rainfall normal (30 year average) of 15 000 mm has been estimated for a small portion of the northwest end of the Pukaki catchment by Kerr et al. (2011), based on rain gauge catches and catchment water balance. However, over most of the country it is between 600 and 1500 mm yr^{-1}. Some areas with an average rainfall under 600 mm yr^{-1} are found in the South Island to the east of the main ranges. North Island mountains are lower, and annual rainfall is more uniform. Much of the island receives about 1500 mm yr^{-1}, and the dry areas (central and southern Hawke Bay, Wairarapa and Manawatu) about 700 mm yr^{-1}.

Evapotranspiration varies less from place to place; annual rates are on the order of 460–1100 mm yr^{-1} (Woods et al. 2006). Evapotranspiration is therefore relatively small in comparison with precipitation in the Southern Alps, but large in comparison with precipitation in the drier east of the country. In summer, in particular, potential evapotranspiration can exceed precipitation for several months.

Reflecting these differences between precipitation and evapotranspiration, rivers draining westwards from the Southern Alps have annual runoffs of the order of 5000 mm, whereas those draining the Wairarapa have annual runoffs of the order of 200 mm. Nationwide estimates of annual runoff using this approach have been published by Woods et al. (2006).

The greatest seasonal contrast in rainfall occurs in Northland, East Cape and the Wairarapa, where winter rain is almost double that of summer. The resultant effect on stream flows is evident from the patterns of monthly flow of the Awanui, Motu and Waipaoa River (Figure 5). This predominance of winter rainfall diminishes southwards, although it is still discernible over the northern part of the South Island and its effect can be seen in the flow of the Buller River (Figures 2A and 4). Further south, winter is the season with lowest precipitation, and inland areas receive most rainfall in summer, from convective showers. The effect of low winter precipitation can be seen in the Taramakau River (Figure 4), but its higher summer rainfall is more commonly due to northwest rainfall than convective showers. The highest variations in seasonal rainfall from year to year are in areas to the east of the mountain ranges. Here very dry conditions may develop in late summer and autumn, particularly in Hawke's Bay, Marlborough, Canterbury, and North Otago. The Hakataramea River monthly flows (Figure 4) and the Whareama River hydrograph (Figure 2D) illustrate the effect of these high seasonal variations in rainfall, and the high rates of evapotranspiration during the summer months.

Usually it rains hardest where it rains the most (Tomlinson 1980; Whitehouse 1985). The highest 24-hour rainfall on record is 758 mm, which fell at Prices Flat in the Hokitika catchment, in the high rainfall zone of the western Southern Alps (Henderson and Thompson 1999). A storage rain gauge at Alex Knob on the south bank of the Waiho River, Fox Glacier, recorded 1800 mm in 3 days in March 1982. If rainfall at Alex Knob has a similar intensity pattern to that at neighbouring recording rain gauges, and we think it does, then about 1350 mm would have fallen in 24 hours (Henderson and Thompson 1999). Such high and intense rainfall produces frequent flashy floods imposed upon a sustained base flow, as is evident in the hydrograph of the Ahaura River (Figure 2B).

The Gisborne and Auckland regions, which have considerably lower annual rainfalls than the Southern Alps, can also receive heavy daily falls of up to 140 mm. In contrast, the plains of Otago and Southland rarely receive daily falls greater than 100 mm and 80 mm respectively (Thompson 1987, 2002).

Interannual Variability — The eastward passage of anticyclones and low-pressure troughs across New Zealand, the weather pattern responsible for the sequence of rainstorms and dry periods normally experienced, is influenced by the state of the El Nino-Southern Oscillation (ENSO). During an El Nino phase, sea surface temperatures around New Zealand are lower and the westerly winds are stronger, resulting in greater rainfall in the south and west of New Zealand and lower rainfall in the northeast. La Nina conditions tend to give warmer sea surface temperatures around New Zealand and lead to fewer westerly winds. This leads to less rainfall in the south and west and more in the northeast (Mullan 1995).

The Interdecadal Pacific Oscillation (IPO) is a decadal-scale oscillation of temperatures within the Pacific Ocean. Shifts in the IPO alter the frequency of occurrence and intensity of El Nino and La Nina phases of ENSO. This oscillation shifted phase in the mid-1940s, again in 1977/1978 (Salinger et al. 2001), and again in 1999 (McKerchar and Henderson 2003). McKerchar and Henderson (2003) investigated whether the IPO affected high and low flows in New Zealand. They found less severe floods occurred between 1978 and 1999 in the Bay of Plenty region and more severe floods occurred in the south and west of the South Island. No consistent changes in flood frequency were found elsewhere in New Zealand. They also found, for 1978 to 1999, that low flows have generally increased in the South Island, particularly in the south, but not in the North Island compared with 1947 to 1977. Analysis of inflows to the South Island hydro lakes indicates that for 2000-2012 inflows are more like those for the mid-1940s to 1977/79 phase of the IPO than for the 1978 to 1999 phase (McKerchar, pers. comm.). McKerchar and Henderson (2003) note that, contrary to previous assumptions, some hydrology statistics are not stationary, and instead change at timescales of 20–40 years. The changes they found in some parts of New Zealand are relatively large and need to be taken into account when planning flood structures such as spillways and stop-banks, or abstractions for water supply or irrigation.

Geological influences

Some types of rock transmit water horizontally much more readily than others, i.e. their transmissivity, defined as the rate at which water moves horizontally through the ground for a unit water table gradient, is higher. Similarly, some types of rock store groundwater in greater volumes than others, because their porosity is greater. Hence, the type of rock, or the lithology, in a catchment, controls the way in which rainfall passes through the catchment to the river. For example, Tertiary mudstones, shales and siltstones have low transmissivity and little storage, and tend to produce flow regimes that have flashy floods, steep recessions, and low base flows. Rocks of this type occur in the Whareama River catchment, in the Wairarapa (Figure 2D). Catchments with high infiltration, transmissivity and water storage tend to have small floods with slowly receding flow, and high, persistent base flows. Examples are the Maryburn River in the McKenzie Basin, which has deep permeable gravels at the surface, or the Rangitaiki River (Figure 5), which drains an area with a deep pumice cover.

In his study of summer low flows in Northland, Waugh (1970) found that fissured basaltic lava absorbed rainfall and released it slowly, thus sustaining low flows. Areas with other rock types such as Cretaceous shale and sandstone were less absorbent, and their streams had lower low flows. A study of water resources of the Nelson area (Scarf 1972) showed that the rivers draining from the marbles of the Mt Arthur Range had substantial low flows, some issuing from caves (e.g. Riwaka River) and springs (e.g. Pupu Springs near Takaka). This was in contrast to the very low flows of streams draining areas covered by the relatively impervious Moutere outwash gravels, where streams commonly dry up in summer. Although rainfall distribution plays a part, catchment geology has a major influence on Nelson flow regimes.

Lake storage has an effect on flow regimes that is similar to that of rocks with high storage characteristics. For example, the Buller River at the outlet of Lake Rotoiti (Figures 2A and 3) shows flow peaks that are much more subdued than those of the Ahaura River, because of the damping effect of the lake.

The role of wetlands

Wetlands are places in the landscape where the soil is permanently wet and there may be standing water. Water sources are ground water seeping to the surface where there are changes in land slope or in topographic hollows. Lakes and rivers may have wetlands on their margins. Wetlands are effective in removing suspended solids, phosphorus, and nitrogen from overland flow (Brauman et al. 2007). It is the macrophytes and microbes common in wetlands that promote denitrification and other biochemical processes for improving water quality.

The role of wetlands in flow regulation is generally poorly understood. Riparian vegetation can play an important role by reducing direct routing to water bodies as well as promoting infiltration. Flood plain wetlands also reduce flooding by absorbing and slowing floodwaters. Headwater wetlands, however, are more unpredictable. Although wetland vegetation impedes flow, the saturated subsurface has no available pore space to absorb water and therefore quickens surface flow. Overall, downstream flood risk is likely to be reduced by maintenance of intact forests and upland wetlands (Brauman et al. 2007).

Human influences

Hydroelectric power — In many New Zealand rivers the natural flow regime has been altered, particularly by hydroelectric power projects or changes in land use. Hydroelectric development has substantially affected the Waiau (Southland), Whanganui, Waikato, Clutha and Waitaki systems. The mean flow of the Waiau River has been reduced from 561 to 157 $m^3 s^{-1}$ by the 404 $m^3 s^{-1}$ of flow that has been diverted to Doubtful Sound via the Manapouri Power Station. The flow regime of the Waiau River at Tuatapere consequently has been affected by a reduction in the full range of flows (Figure 6).

Some of the headwater streams of the Whanganui River have been diverted into the top of the Waikato River system – much of

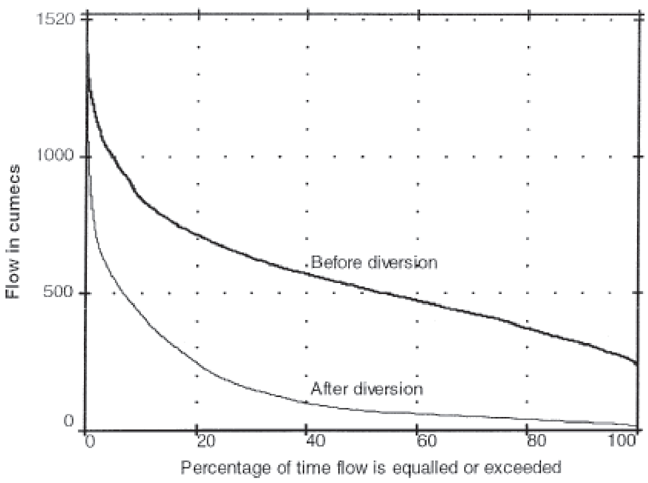

FIGURE 6 Flow duration curves of the flow in the Waiau River at Tuatapere before and after diversion via Lake Manapouri to Deep Cove.

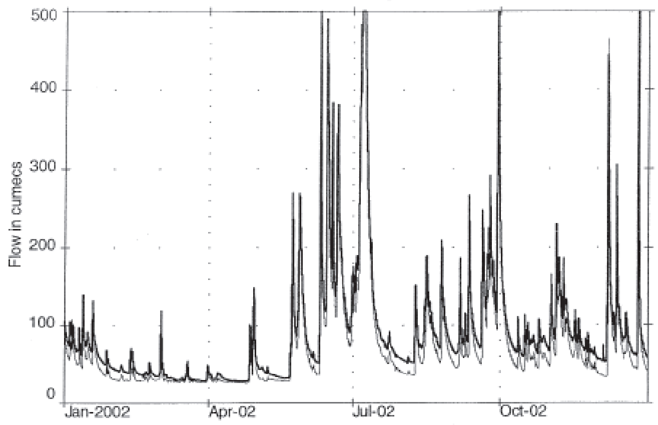

FIGURE 7 Flow recorded in the Whanganui River at Te Maire (fine line) and flow that would have occurred without the diversion (thick line). To protect the in-stream environment, diversions are reduced between December and May, and cease altogether when the flow is less than the mean annual low flow (e.g. as illustrated in March and April).

their low and median flows are now redirected, leaving only small residual flows and flood flows. However, the normal regime of the Whanganui is partially restored as undiverted tributaries add to its flow. Hydrographs of the remaining flow and simulation of the natural flow of the Whanganui River at Te Maire (Figure 7) illustrate that the low flow part of the flow regime is most affected by the diversion, but to protect important features of the instream environment, between December and May, diversions must stop when flow is less than the mean annual low flow. The loss of 18 $m^3 s^{-1}$ from the Whanganui River system is the Waikato River's gain. The Waikato also gains 14 $m^3 s^{-1}$ from the Rangitikei River via the Moawhango Tunnel. It is further modified by controlled outflows from Lake Taupo and eight hydroelectric power stations further downstream. The net effect has been to reduce flood flows and increase low flows in the Waikato River.

At the Roxburgh hydroelectric power station, the release of extra water from Lake Roxburgh to meet peak electricity demands produces a daily flood wave on the Clutha River (Figure 8). It has been suggested (Otago Catchment Board 1986) that this, combined with the tidal and wave pattern at the coast, has resulted in periodic shifts of the river mouth, leading to regular flooding in the Lower Clutha delta. The monthly Clutha flows (Figure 4) mask the daily fluctuations. The monthly regime is fairly even through the year because of the moderating effects of the large lakes Wakatipu and Wanaka and the manipulation of water storage in Lake Hawea.

Hydroelectric storage dams and diversion canals in the Waitaki Catchment have made dramatic changes to the flow regimes of its large rivers. The Ohau River previously had a mean flow of 80 $m^3 s^{-1}$, but now has either no flow or occasional flood flows. However, agreement has been reached on releasing a residual flow of 10 $m^3 s^{-1}$ in exchange for being able to operate Lake Ohau over a larger range of lake levels. The Pukaki River now has no flow and there are only occasional flood flows in the Tekapo River. The Tekapo River further downstream is now much clearer than before and conditions for trout have been enhanced (Teirney et al. 1982). Flood flows have been reduced and low flows increased in the lower Waitaki River. However, the Roxburgh and Waitaki dams have prevented chinook salmon from returning to their previous spawning grounds, and the salmon runs are reported to have been substantially reduced (Teirney 1980).

Irrigation and water use trends — Irrigation is the largest consumptive use of water in New Zealand with 46% of allocated consumptive water use. (The other major consumptive use at 41% of total allocation is the Manapouri Power Station, which discharges water to sea). About 60% of irrigation water is taken from surface water sources, 35% from groundwater, and the remainder from storages. Irrigation occurs mainly in the drier east of the country with Canterbury and Otago using most irrigation water. National water allocation increased by a third between 1999 and 2010, with allocations, predominantly for irrigation, nearly doubling between 1999 and 2010 and with a 10% increase between 2006 and 2010 (Figure 10). The largest increase of 65% for 1999–2010 was in Canterbury. The amount of land irrigated by consented water takes has increased by 82% between 1999 and 2010. Actual water use averages about 65% of consented volume.(http://www.mfe.govt.nz/environmental-reporting/freshwater/demand/).

Dairying is driving the demand that is also occurring in Manawatu-Whanganui, Northland, and other areas that have traditionally relied on rainfall to sustain grass growth. Irrigation abstraction changes natural flows and regulates flows by reducing flows from spring through to autumn. Storage of irrigation water in dams is becoming more important as surface water resources for run-of-river irrigation schemes become fully allocated. Inflows to storage can occur during autumn and winter and in summer when water is not required for irrigation, e.g. after heavy rain. So, irrigation schemes relying on dams have the potential to affect flow regimes more than run of river schemes. If irrigation rates exceed the water-holding capacity of the soil, as sometimes happens with border dyke irrigation, then some irrigation water may flow into streams as "bywash", increasing the flows in the receiving stream during the irrigation season, and possibly also carrying nutrients and contaminants such as faecal coliform bacteria to the stream. Resource consents usually limit abstractions to leave a residual flow, variously set as the mean annual low flow or the 5-year low flow, or some other ecologically relevant flow. Often this leaves the stream with an undesirable, relatively constant, low flow throughout most of the summer, but some resource consents specify a sharing rule to maintain a degree of flow variability within the range affected by abstraction.

For example, the Rangitata diversion race takes up to 32 $m^3\ s^{-1}$ from the Rangitata River, under a 1:1 sharing rule, for irrigation from September to April and for hydro-electricity generation during the balance of the year. The abstraction does not alter flow variability much, but low flows are reduced to only half the natural flow for significant periods of time (Figure 9). Alternatively, a flushing rule may be introduced to allow freshes and floods to pass down the river without abstraction for 24 hours to flush filamentous algae and silt from gravels and so maintain the periphyton and benthic invertebrates that would normally be expected in the river.

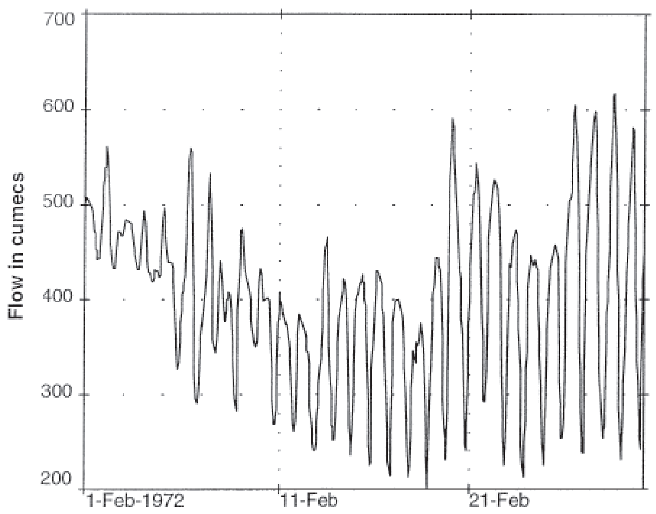

FIGURE 8 Daily flood waves in the Clutha River at Balclutha, caused by the response of Roxburgh hydroelectric power station to varying demand for power.

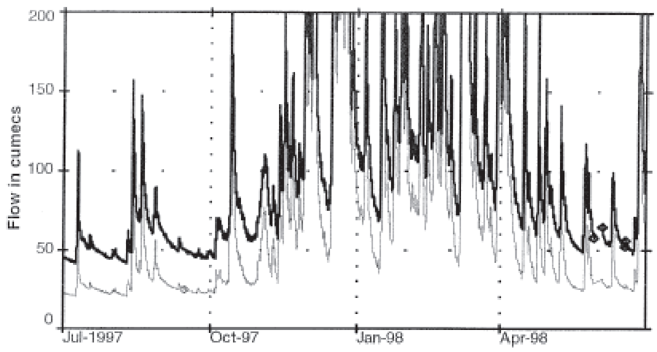

FIGURE 9 Flow recorded in the Rangitata River in a typical year (thick line). The fine line shows the residual flow in the river after abstraction of water for irrigation in summer and hydropower in winter.

Changes in land use — Both Maori and European settlers in New Zealand have influenced river flow regimes by making large-scale modifications to the vegetation. Before human settlement about 80% of New Zealand was covered in predominantly tall podocarp and beech forest. By about 1950 the amount of indigenous forest had declined to about 23% and has remained relatively static since. The moa hunters effectively converted large areas of forest to tussock country by burning. Europeans in turn have converted tussock, scrub and forest country to pastoral farms, and forest and scrub country to pine plantations. Exotic forest, whose main forestry tree is radiata pine (*Pinus radiata*), covered about 7% of the total land area in 2002. There has been little increase since then (Fahey et al. 2004).

When land is cleared of scrub or forest, runoff from the land increases markedly, thus increasing floods and low flows. When mature pine plantations replace pasture, flood peaks may decrease by up to 80% and annual yields and low flows can halve (Figure 1); the opposite happens when pasture replaces pines. Annual flow changes when catchment cover changed from pasture to mature pine forest covering the whole catchment range from 44% to 66% of annual rainfall with higher rainfall areas having the lowest percentage reductions and highest measured reductions in runoff. Afforestation of pasture in large catchments (e.g. the 906 km^{-2} Tarawera catchment) has the same relative effect as in small catchments (Dons 1986), although such large catchments are seldom completely afforested. These changes in the hydrology occur primarily because of differences in interception of rainfall, rooting depth and evapotranspiration by different types of vegetation. Interception is the rain which falls on vegetation and does not reach the ground. It is usually evaporated and thus not available for transpiration by the plants or for runoff. Rowe et al. (1999, 2002) showed that mānuka and kānuka scrub may intercept 42% of rainfall, beech-podocarp forests 30%, Douglas fir plantations 29% and radiata pine plantations 23%.

The effects of afforestation of grassland on water yield has been of concern to some regional councils, which have introduced rules into regional or district plans to restrict afforestation on catchments that are either sensitive to land use change or

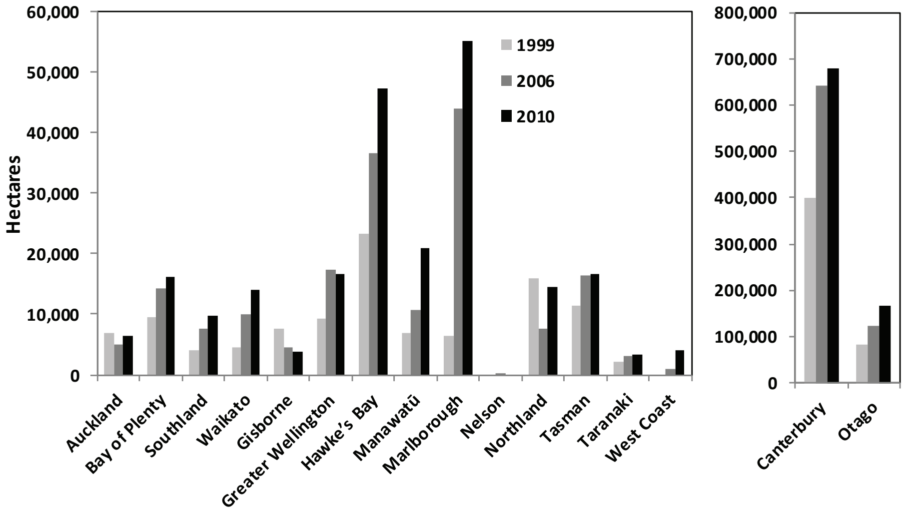

FIGURE 10 Consented irrigated area takes by region. Source: Aqualinc (2010).

where afforestation may affect groundwater recharge. The reason for the rules is the likelihood that afforestation would affect the flow regime, with reduction of flows lower than the mean flow being the main concern. The issue being that the flow loss could reduce the reliability of supply of water to holders of consents to abstract for irrigation or reduce the life supporting capacity of the rivers.

Man-made rules — Most regional councils have regional, district or catchment specific plans, that specify allocation rates and minimum flows. The flow of water is also regulated by conditions attached to resource consents. Some regional or district councils also have land use controls that control land cover which in turn regulates river flows. Water Conservation Orders to preserve outstanding features of rivers can prevent abstractions in some parts of a river or limit water abstractions in other parts. Resource consents can further specify controls on the amount and timing of abstractions. Most surface water abstraction consents specify a minimum flow below which the flow is not allowed to fall due to the abstraction. The minimum flow is usually set to provide for the life supporting capacity of the biota living in the particular river. It may also be set at a level that allows passage for migrating adult salmon, and navigation for kayaks, or jet boats, if appropriate for the river. These flows may not necessarily be the preferred flows for salmon angling or boating. Limits are increasingly being set on the amount of water that can be abstracted. In the past that limit was often set at a level that would allow a high reliability of supply for municipal or run-of-river irrigation use. This allows many rivers to retain much of the flow variability necessary for flushing periphyton and silt, providing temperature, turbidity or flow signals for migrating fish, contributing to maintaining river mouth openings, transporting sediment to contribute to maintaining river morphology, preventing invasion of the river bed by woody species and contributing to coastal sediment budgets.

With most surface water resources in irrigation areas now being fully allocated, plans are being made for storage of less reliable water from the more variable parts of the hydrograph, and for water allocated but not being used. Allocation of this water has to be carefully considered or the environmental factors that flow variability contributes to can be compromised. Damming of main stem flows and significant tributaries can compromise most of the factors that flow variability affects, e.g. the damming of the Waitaki River has changed an intensely braided river with bare gravel bars and relatively shallow flows to a woody-weed-infested river bed with fewer, deeper and more stable channels. Resource consent conditions specifying the size and frequency of flushing and flood flows can mitigate the worst of these effects.

Some regional councils in areas with seasonal soil water deficits are concerned that afforestation of pasture and tussock covered headwater catchments will reduce the reliability of supply for downstream irrigators and compromise instream ecological values. Tasman District Council restricts afforestation in parts of the district to 20% of each land title and currently Canterbury Regional Council restricts afforestation so that catchment low and mean flows will not be reduced by more than 5% and 10% respectively by the afforestation of short grassland in listed catchments that are deemed sensitive to land use change. The rule is under review at the time of writing but some afforestation restrictions are likely to remain.

There are draft national environmental standards (NES) for ecological flows (MfE 2008) that specify for surface waters that if no other data is available then water allocation for rivers and streams with mean flows less than 5 $m^3\ s^{-1}$ should be limited to 30% of the mean annual low flow (MALF) and the minimum flow should be 90% of the MALF. For larger rivers the minimum flow should be 80% of MALF and the allocation 50% of MALF. This chapter has shown that flow regimes vary rather widely and a blanket standard such as those proposed is not appropriate and could lead to under allocation of some rivers, such as spring-fed streams and large rivers, and over allocation in others, if it was widely adopted. Snelder et al. (2011) have investigated the proposed rules and found that they result in inconsistent consequences for the protection of ecosystems and the reliability of water resources. The draft NES default limits tend to underestimate the sensitivity of small rivers to reductions in flow.

ESTIMATING FLOW REGIMES OF UNGAUGED CATCHMENTS

Stream flows have been measured for only a limited number of rivers and streams in New Zealand. It is often necessary, however, to estimate the magnitude of floods and low flows for rivers that do not have a stream flow record. To do this, hydrologists have used regions in which river basins are sufficiently similar to apply the measured relationships between rainfall and runoff from gauged basins to ungauged basins. The high variability of geology, topography, and especially rainfall in New Zealand, makes the definition of 'hydrological' regions a difficult task.

Regionalisation

Toebes and Palmer (1969) divided New Zealand into 90 regions based on geology and climate, and proposed that representative basins monitoring rainfall and runoff be established in each region. Fifty-three regional basins (Duncan 1987) were instrumented and, together with those rivers instrumented for flood warning, power, or irrigation development, served as the basis for flow estimates.

In the North Island, where regional geology and soils vary more than in the South Island, cluster analysis suggested that useful regions could not be easily identified (Mosley 1981).

Beable and McKerchar (1982) proposed regions for the estimation of flood size and frequencies based on regional equations. They defined 7 and 6 regions, respectively, in the North Island, and 6 and 3 regions in the South Island. While this was a useful exercise, difficulties arose at regional boundaries, where flood estimates could vary widely depending on which regional equation was adopted.

A later study, using a larger data set and longer records, demonstrated that contour maps of mean annual floods and 100-year average recurrence interval floods could be drawn for the whole country (McKerchar and Pearson 1989). Flood flow regimes varied smoothly across New Zealand, rather than abruptly changing at sharply-defined regional boundaries.

Equations for estimating the low flow of ungauged catchments, based on 11 regions nationwide, were proposed by Hutchinson (1990). Many regional equations were quite similar, with the differences justified by providing more precise estimates. Paradoxically, the Southern Alps region and North Island central volcanic plateau, regions of quite different geology and rainfall regime, had similar equations for the estimation of low flows. The regular Southern Alps rainfall and the porous volcanic plateau bedrock both have the effect of sustaining low flows.

Pearson (1995) used annual minimum low-flow series from nearly 500 catchments nationwide to draw contour maps of specific mean annual 7-day low flow. He also used catchment characteristics (e.g. area, annual rainfall, vegetation, elevation, % bare land, slope, and hydrogeology index) from a subset of sites with longer records to predict mean annual 7-day low flows. These two methods were adequate to predict regional variations in low flows, but the catchment characteristics method was biased for catchments with low specific discharges.

Flow variability was the basis for the classification of 130 river sites by Jowett and Duncan (1990). They did not attempt to map hydrologic regions but they did identify six groups. Rivers with the lowest flow variability were associated with the large South Island montane lakes because the lakes attenuate the flows, and with the volcanic plateau of the North Island, where precipitation is absorbed by the porous pumice lithologies and emerges evenly in springs. The next group was also in the central portions of the North and South Islands where regular, but not constant, precipitation, resulted in a relatively constant base flow. The group with the greatest flow variability was on the east coast of both islands, where rainfall is irregular and low in relation to evapotranspiration. Here summer flows are very low, and winter flows are quite high, as the underlying geology has low transmissivity and little storage, so once the soil is saturated a large proportion of the precipitation runs off. An intermediate group included rivers around Mt Taranaki, the Tararua Ranges, and in the Nelson region.

Because of their links with biological communities, rock type (soft and hard sediments, igneous rocks, volcanic ash), flow variability, and water quality (mainly conductivity) were the basis of defining regional groups of rivers to form riverine "ecoregions" in a study by Biggs et al. (1990). Five principal riverine ecoregions were distinguished. Particularly distinctive were the hydrological, geological and water quality conditions of the central North Island volcanic plateau and the eastern, Hawke's Bay–Poverty Bay region of the North Island. Other regions were the Tararua Ranges, the remainder of the North Island comprising Taranaki, Waikato and Northland, and the South Island. Defining such regions could have considerable benefits for establishing river management goals, especially where unmanageable factors such as catchment geology may cause naturally poor water quality compared with other regions. Many of these ideas have been incorporated into the River Environment Classification discussed below.

In summarising regional hydrological regimes, Mosley (1981) stated that in the South Island, climatic regime, as modified by topography, appears to be the major influence. Much of the South Island is underlain by relatively impermeable rocks, and has steep topography. They are less important as sources of a variation in flow regime than climate, which is spatially highly variable. The North Island is more complex, with variations in flow regime influenced by climate (e.g. the Northland sites), lithology and soils (e.g. pumice area sites), and topography (e.g. sites draining the Tararua Range and Mt Taranaki).

River Environment Classification

The River Environment Classification (REC) uses a six-step hierarchal approach to describe the main causes of variation in river environments (Snelder and Biggs 2002). At the top of the hierarchy is climate, and then source of flow (SOF). Sources of flow are determined by rules applied to the catchment upstream of each river reach, e.g. glacial mountain sources of flow applies to catchments with >2% of catchment area with permanent snow. Catchments with Glacial Mountain sources of flow have low flows in winter and high flows in spring and summer as the snow melts (Table 1). Other sources of flow are Mountain, Hill, Low elevation and Lake – each one has a characteristic flow regime with different seasonal timing and amplitude of flow regimes, e.g. lake sources of flows have low FRE3, coefficient of variation (CV) of flow and MaxF (Table 1) (Snelder and Biggs 2002). Flow regimes at 335 flow sites nation-wide were described by 13 flow variables. Data were analysed to determine the mean values for 14 climate/source of flow classes. Statistical tests were used to see how well the sites in each class clustered and to see if there was clear separation between the classes. The River Environment Classification

TABLE 1 Hydrological variables for different sources of flow
CVW = cold very wet (mean annual temperature <12°C, precipitation >2200 mm/a); CW = cold wet (precipitation 1200 to 2200 mm/a); CD = cold dry (precipitation <1200 mm/a); WVW = warm very wet (mean annual temperature >12°C); WW = warm wet; WD = warm dry; MaxF = mean annual 7-day high flow/median; Tmin, Tmax = month with the lowest and highest flows where January = 1.

Source of flow	FRE3	CV	MaxF	Tmin	Tmax
CVW, Glacial Mountain	15	1.0	35	6.4	11.8
CVW, Mountain	22	1.3	49	4.8	10.7
CVW, Hill	27	1.7	87	3.08	8.6
CVW, Lowland	27	1.9	115	1.8	7.8
CVW, Lake	2	0.6	8	2.7	10.7
CW, Mountain	13	1.1	48	3.3	9.9
CW, Hill	15	1.5	90	2.4	8.3
CW, Lowland	18	1.9	163	1.9	7.3
CW, Lake	2	0.5	9	2.4	9.6
CD, Hill	11	2.4	366	2.7	8.3
CD, Lowland	14	2.1	165	2.4	6.8
WVW, Lowland	19	1.8	151	2	7.0
WW, Lowland	18	2.3	230	1.2	7.4
WD, Lowland	19	3.2	471	1.9	7.4

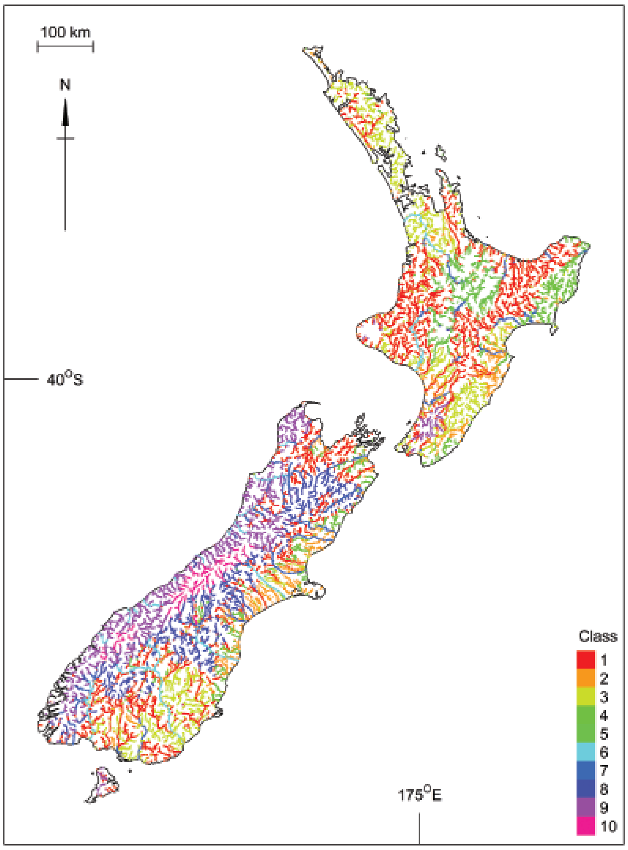

FIGURE 11 An objective classification based on flow statistics of New Zealand rivers where the rivers are evenly divided between classes (from Snelder and Booker 2012).

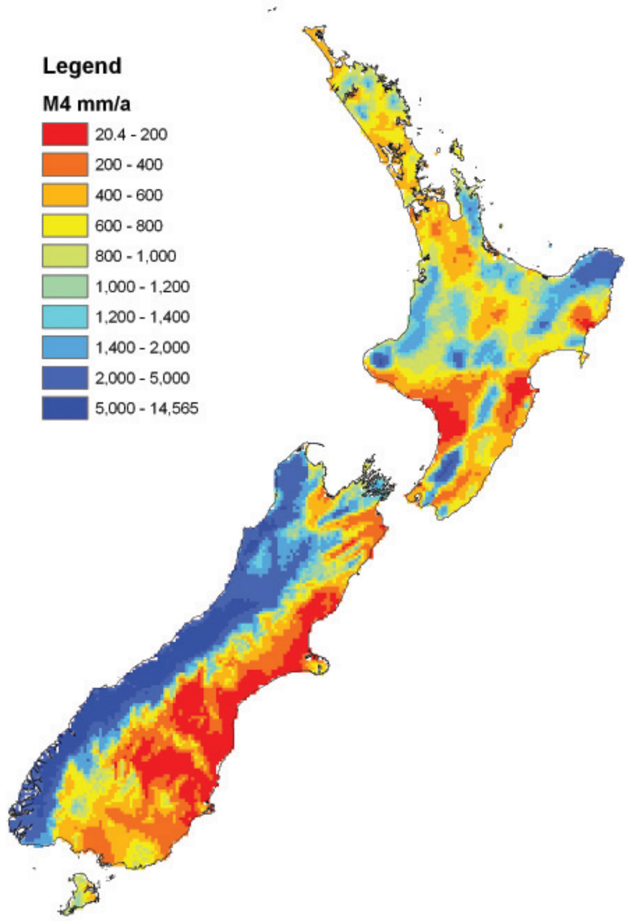

FIGURE 12 A mean flow map for New Zealand based on water balance using estimates of actual evapotranspiration and bias corrections for inaccurate rainfall estimates (from Woods et al. 2006).

was compared with a climate classification, Hutchinson's (1990) classification, and New Zealand water management regions. The River Environment Classification was the strongest predictor of flow regime. However, it was not strong enough to be used reliably to predict the flow regime characteristics of a specific site (Snelder and Biggs 2002).

Flow Regime Classifications

Flow regimes may be classified in a number of ways and the REC is one way, based on expert defined rules. Snelder and Booker (2012) compiled five other classifications defined by using hydrological indices calculated from 321 natural daily flow records. Different classifications were produced depending on the statistical methods used to discriminate between the classes. These were mapped using a digital river network. Figure 11 is derived from a multi-level classification and shows a 10 level classification. Only river orders greater than 3 are shown.

Mean flow mapping

Maps of mean flow for all New Zealand (Figure 12) were developed by Woods et al. (2006) using water balance based on maps derived from daily rainfall series from 1960 to 2001 from 500 locations (Tait et al. 2006) and daily Penman potential evapotranspiration (PET) (Penman 1948) from 70 climate stations (Tait and Woods 2007). The resulting mean annual runoff was compared to measurements and synthesised measurements of runoff from 524 catchments. After changing PET to actual evaporation estimated using Zhang et al. (2004) and using a bias correction for inaccuracy in rainfall, 92% of sites had modelled runoff within 25% of the measured runoff.

Hydrological models

The flow regimes of unmodified rivers can be estimated with hydrological models, using information on climate, vegetation, soils and topography. If human influences are present (e.g. irrigation, hydropower development), then the models will also need to account for these. The choice of modelling approach depends on the amount of data and resources available. For example, summary information on annual and seasonal climate (rainfall, temperature, potential evaporation), vegetation type and soil properties, can be used to estimate annual and seasonal flows. These estimates use very simple models of water balance for the plant canopy, soil water, and shallow groundwater, e.g. Woods (2003).

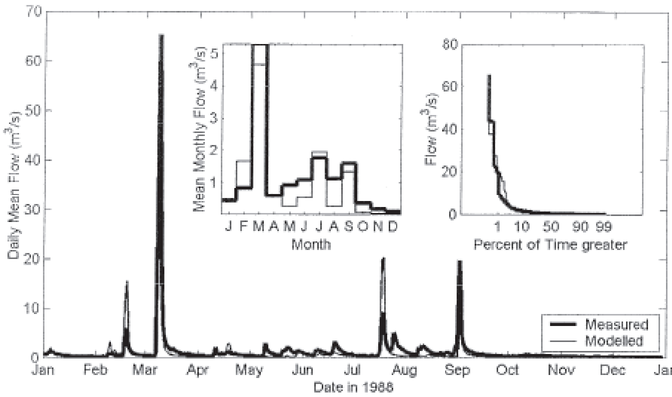

FIGURE 13 Measured and modelled daily flows for the Waikohu River using the TOPNET model. Insets show measured and modelled monthly flows and flow duration curves.

If more detailed information on catchment and climate properties is available, then a detailed catchment simulation model, such as TOPNET (Bandaragoda et al. 2004), can be used to produce modelled daily or even hourly flow hydrographs for ungauged catchments. Figure 13 shows the application of this technique to the Waikohu River, a small (26 km^{-2}) tributary of the Waipaoa River. The model estimates are broadly similar to the measured values, which were not used in the development of the model. Models can always be adjusted to improve the fit to observed flow data. Figure 13 shows what level of accuracy might be achieved by this method if no measured data are available.

CONCLUDING REMARKS

Flow regimes in rivers are regulated primarily by the balance between the seasonality and intensity of precipitation and evapotranspiration. However, the balance is altered by natural features such as vegetative cover, geology and presence of lakes, which can moderate floods and help sustain base flows. Human use of rivers can also change flow regimes by damming rivers for hydropower and irrigation and changing land cover, which can alter the timing and amount of flow. Flow regimes are important because, along with water quality, they influence the plants and animals living in rivers and the way in which people and society can use river water. If the need for water does not coincide with the flow regime, reservoirs may be needed. Flow regimes are so fundamental to human use of rivers, that flow statistics have been developed to classify and describe various aspects of the flow regime and to predict those aspects for ungauged catchments.

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