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River morphology and management in New Zealand

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Abstract: River research in New Zealand is strongly conditioned by management requirements defined by environmental legislation. Principal areas of investigation at present include information on river morphology, habitat and instream flows required for management of fluvial ecosystems; erosion, sediment transport and sediment yield; and gravel-bedded and braided river processes. Research in these areas has tended to have a strong orientation towards field observations as a basis for developing quantitative (commonly statistical) models, and ultimately the provision of guidance material and decision support systems for resource managers. A fourth area of particular emphasis has been channel networks and hydraulic geometry. Again, the work generally has been field-intensive, but has been directed towards testing models such as the optimal channel network concept. Current research directions are focusing particularly on gravel-bed river mechanics, climatic and tectonic controls on landscape evolution, and instream habitat hydraulics and ecosystems.

Key words: channel networks, erosion, gravel bed rivers, hydraulic geometry, instream habitat, river morphology, sediment transport, sediment yield.

I Introduction

New Zealand research into fluvial processes and morphology has been driven to a large extent by river management requirements. These have evolved over time and as relevant statutes have been introduced or repealed. Over the last 50 years, emphases have shifted from a general concern for soil conservation and river control (Soil Conservation and Rivers Control Act 1941), through to integrated catchment and river management (Water and Soil Conservation Act 1967), to a focus on recreational and instream uses (1981 amendment to the 1967 Act), and then to fully integrated resource management (Resource Management Act 1991).

At present, river research, much of which is funded by the New Zealand government's Public Good Science Fund, is very much focused on the information and technology needed by local authorities to discharge their responsibilities under the

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Resource Management Act (RMA) and other statutes. The RMA makes explicit reference to management of the beds of rivers and lakes, and to varying the levels and flows of water courses by abstractions or discharges. However, many of the greatest challenges to river research relate to general provisions of the Act, or to novel aspects of resource management. These include, in particular (sects. 5–7 and 35):

- The requirement to safeguard 'the life-supporting capacity of air, water, soil, and ecosystems'.
- The need to recognize and provide for 'the preservation of the natural character of . . . lakes and rivers and their margins . . .'.
- 'The relationship of Maori (New Zealand's pre-European indigenous people) and their culture and traditions with . . . water . . .'.
- The need to have particular regard to 'the maintenance and enhancement of amenity values', 'intrinsic values of ecosystems', and 'the protection of the habitat of trout and salmon'.
- The statutory requirement on local authorities to gather information on and monitor the state of the environment.

In response to these requirements, much recent and current river research has a strong ecological flavour. This is reflected in the recent publication of management handbooks and guidelines such as *Managing riparian zones* (Collier *et al*., 1995), *Flow guidelines for instream values* (Ministry for the Environment, 1998) and *Environmental indicators for the sustainable management of freshwater* (Ward and Pyle, 1997). In addition, channel hydraulics, erosion/sedimentation and sediment transport continue to receive attention because of their relevance to catchment and river management (under the 1941 Act), while a variety of other more 'specialist' areas also feature in the current New Zealand portfolio of river research. This review article focuses on those areas which have been receiving the heaviest investment of effort in recent years, namely:

- River morphology, habitat and instream flows.
- Erosion, sediment transport and sediment yield.
- Channel networks and hydraulic geometry relations.
- Gravel-bedded and braided-river processes and morphology.

General reviews of fluvial processes and morphology have been provided by Mosley (1992) and Mosley and Duncan (1992), while Carson and Griffiths (1987), Hicks and Griffiths (1992) and Hicks and Davies (1997) have reviewed fluvial sediment transport.

II River morphology, habitat and instream flows

The physical characteristics of a river and the way in which these change with flow are important in determining the abundance and diversity of the fauna and flora. The morphology of a river determines its habitat – factors such as the water depth, velocity, substrate and instream cover – and these in turn influence the fauna and flora. At-a-station hydraulic geometry relationships and instream habitat surveys both predict how stream depth and velocity change with flow. The main difference is that hydraulic geometry predicts average depths and velocities, whereas instream habitat methods predict values at measurement points. Despite this difference, at-a-station hydraulic geometry can be used to predict whether river flows provide suitable habitat within reasonable levels of accuracy (Jowett, 1998).

River management needs have encouraged research on habitat requirements, habitat modelling and validation studies, and the influence of flow regime on river ecosystems. During the 1980s, a broad-ranging study of the hydrological, biological, chemical and physical characteristics of New Zealand rivers provided baseline data and a starting point for more recent research on stream morphology, instream habitat, and periphyton and fish communities ('100 rivers' study – Biggs *et al.*, 1990).

1 Habitat suitability

Habitat suitability curves have been developed for brown trout (Hayes and Jowett, 1994), rainbow trout (Jowett, Rowe *et al.*, 1996), most common New Zealand native fish (Jowett and Richardson, 1995) and benthic invertebrate species (Jowett *et al.*, 1991), and even for a species of duck (Collier and Wakelin, 1995). Comparisons of habitat preferences between rivers (Jowett *et al.*, 1991; Hayes and Jowett, 1994) show that preferences are generally consistent between rivers, and any differences can usually be attributed to small sample sizes or the relative availability of habitat types in the different rivers. However, habitat suitability curves for trout in New Zealand differ from those developed in North America. New Zealand brown trout are most commonly found where water velocities are about 0.4 m/s (Hayes and Jowett, 1994) and rainbow trout in velocities of 0.6 m/s (Jowett, Rowe *et al.*, 1996), whereas velocity preferences given in North American literature are usually lower, possibly because of differences in fish size. New Zealand native fish also show similar size-related differences in habitat use, although habitat suitability curves have not been derived for different fish sizes.

2 Validation of instream habitat methods

The ecological goal of instream habitat methods is to provide a suitable physical environment for the organisms that live in the river. Although the assumption of a relationship between abundance of biota and habitat has been questioned (Scott and Shirvell, 1987), it is obvious that if there is no suitable habitat for a species it will not be able to exist. However, the selection of appropriate habitat suitability curves and consideration of other factors, such as food, water temperature and quality, and flow regime, are essential for successful river management. Studies in New Zealand have shown relationships between instream habitat and fish and benthic invertebrate abundance, but have shown that other factors also influence abundance.

A national survey of adult brown trout abundance and habitat in 59 rivers showed a relationship between habitat and the density of fish. There was a positive ($r^2 = 0.38$, $P < 0.005$) correlation between adult trout numbers and the amount of habitat at mean annual low flow (Figure 1). The study showed that other factors, especially the amount of instream cover and the density of benthic invertebrates (trout prey), were also important. A regression model incorporating adult brown trout habitat, food-producing

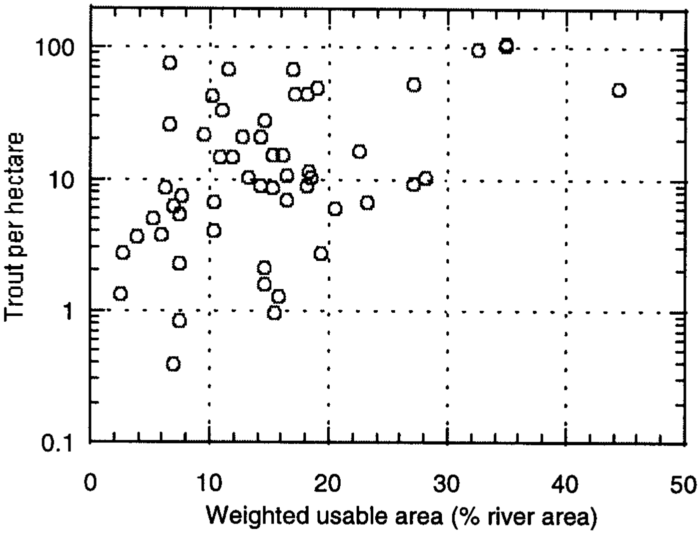


Figure 1 Relationship between density of large brown trout (> 20 cm) and instream habitat (weighted usable area) for 59 New Zealand rivers

habitat, instream cover and six other variables explained 87.7% of the variation in adult trout density (Jowett, 1992). It also predicted trout density along a 55 km long stretch of river within the limits of annual variability (Jowett, 1995).

Habitat suitability curves for native fish were developed in larger rivers where it was possible to sample a range of depths and velocities. These showed that native fish were most abundant in shallow water (< 0.4 m), often with moderate velocities (< 0.4 m/s) (Jowett and Richardson, 1995). This preference for shallow, moderate velocity water was corroborated in small tributaries of the Grey River, where the density of native fish species was highest in streams where the average depth and velocity were close to the habitat preferences of the species (Jowett, Richardson *et al.*, 1996).

The relationship between invertebrate animals and aquatic habitats has also received considerable attention because they provide an important food source for sport fish. Some invertebrate species have well defined habitat preferences and others seem to be found anywhere. For example, snails are most abundant in slow-flowing areas whereas stonefly larvae and some Diptera (*Aphrophila neozelandica*) are most abundant in swift water (Jowett *et al.*, 1991). For these species, there are good correlations between habitat suitability and abundance. However, for some other species such as cased caddis (*Olinga feredayi*) abundance is less closely related to habitat.

3 Application of instream habitat assessment methods in New Zealand

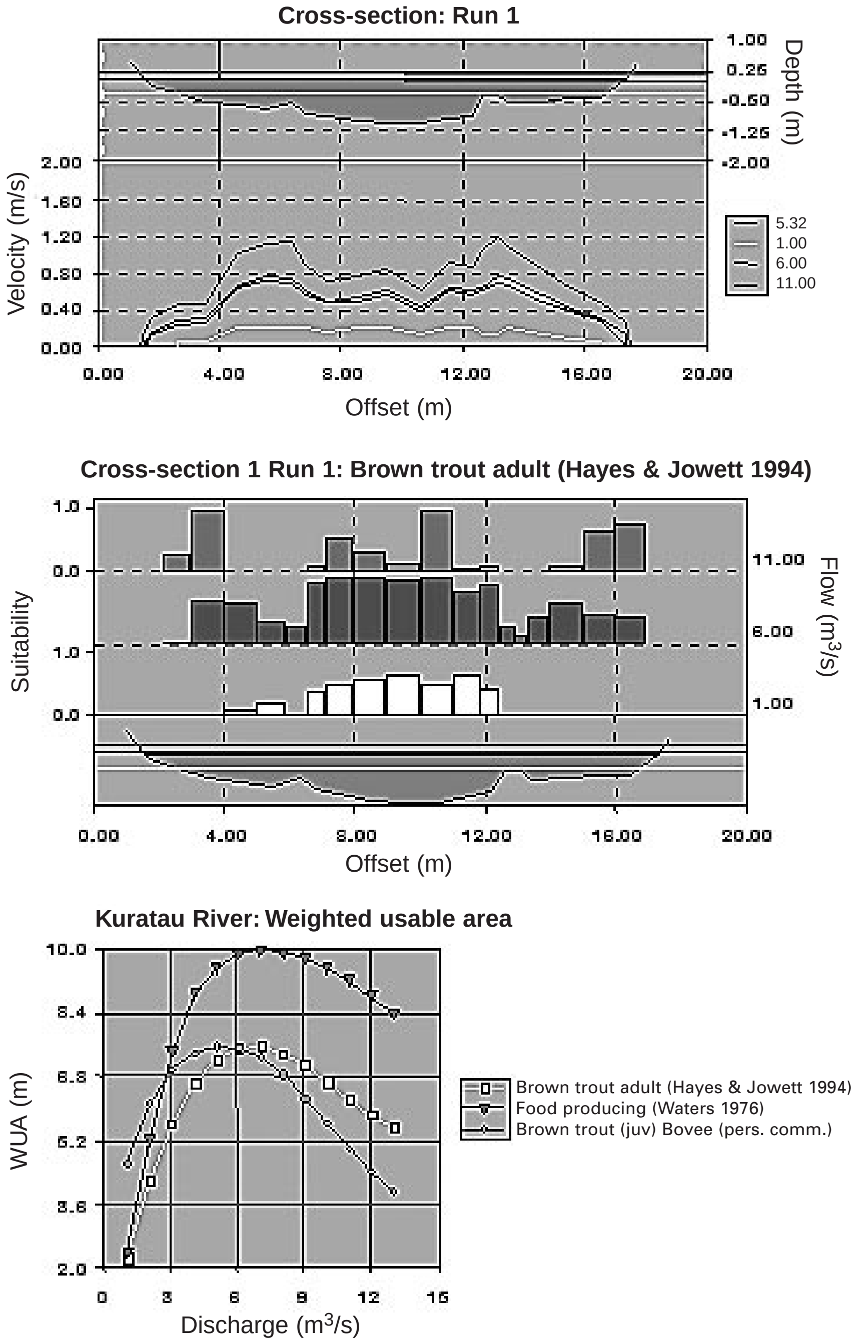
In New Zealand, instream flow management is a political process where issues are resolved by consensus as far as possible, using the RMA as a framework. The Ministry for the Environment (1998) has set out some guidelines for this process, in which the important steps are to identify the value of the instream and out-of-stream water resource, specify the instream values that are to be sustained and define the instream management objective and flow regime requirements.

Instream habitat methods for assessing environmental flow requirements have been used in many of the major water resource allocation exercises because they are more defensible under the RMA than other flow assessment methods. Since 1978, instream habitat surveys have been made at more than 170 sites in New Zealand. Usually these surveys were carried out to determine flow requirements for trout, native fish or birds, and stream insects using RHYHABSIM (Figure 2). Unfortunately, there has been no scientific monitoring of the biological result of flows based on instream habitat assessments, but anecdotal information and the lack of obvious environmental degradation after flow recommendations have been implemented suggest that results are satisfactory. For example, in New Zealand's premier rainbow trout fishery, the Tongariro River, the objective was to optimize the flow regime for production of juvenile trout and catch rate of adult trout. Angling habitat was determined by measuring the hydraulic characteristics of well-known fishing lies, and juvenile habitat was determined by electric fishing. Habitat preferences were determined by comparing angling habitat, habitat utilized by juvenile trout, and available habitat. It was concluded that the existing modified flow regime was close to optimum for adult trout habitat and angling, while seasonal flow variations might improve juvenile trout habitat and productivity (Jowett, Rowe *et al.*, 1996). This was in agreement with anecdotal information that the modified flow regimes had not been detrimental to the fishery.

4 Flow regime requirements

In New Zealand there are large differences in flow regime over short distances and this influences the development of biota in New Zealand rivers (Jowett and Duncan, 1990). Rivers require more than just a 'minimum flow', and some degree of flow variability is desirable. This view is supported by a study (Jowett, 1992) which showed that brown trout abundance was related to the amount of trout habitat at minimum flow and to the amount of food-producing habitat at median flow, suggesting that a minimum flow might provide habitat but would not generate enough food for the trout. Life history requirements can also depend on flow variability, with floods resetting the 'biological clock' by flushing fine sediment deposits from the substrate (Jowett and Richardson, 1989) and providing a stimulus for renewed or different biological activity (e.g., Rounick and Winterbourn, 1983). Floods also play an important part in the diadromous life-cycle of New Zealand native fish by carrying larval fish to the sea before their eventual return to adult freshwater habitats. Some of the whitebait species (*Galaxias* spp.) lay eggs on vegetation or exposed stream substrate along stream margins or on instream debris, and floods carry larval fish or eggs to the sea (Ots and Eldon, 1975).

Floods are classed as 'disturbances' – a term which is particularly appropriate because one of their main effects is the disturbance of the stream bed. Although the intermediate disturbance hypothesis (Connell, 1978) suggests that streams with an intermediate level of disturbance will contain more invertebrate species than either streams with frequent flooding or streams that flood infrequently, New Zealand studies suggest that invertebrate abundance is highest where there is an intermediate level of


Cross-section: Run 1

Cross-section 1 Run 1: Brown trout adult (Hayes & Jowett 1994)

Kuratau River: Weighted usable area

Figure 2 Example of habitat analysis using RHYHABSIM showing the prediction of water level and velocity for flows of 1–11 m^3/s (top), the evaluation of habitat suitability for adult brown trout (centre), and the summation of habitat suitability as weighted usable area for all cross-sections (bottom).

disturbance (Quinn and Hickey, 1990; Death and Winterbourn, 1995). Clausen and Biggs (1997) investigated a series of measures of flow variability and concluded that the annual frequency of floods greater than three times the median flow (FRE_3) was an ecologically useful indicator. This index also appealed to ecologists because of its clear association with floods and their effect on fish and benthic invertebrate populations in rivers. Clausen and Biggs (1997) defined an intermediate level of disturbance as a FRE_3 of 10–15.

The effect of floods on stream biota is largely a result of the high water velocities and substrate movement during flood, that displace or kill aquatic species (Jowett and Richardson, 1989; Scrimgeour and Winterbourn, 1989). Floods remove periphyton (algae attached to substrate) from rivers, although in many New Zealand rivers physical abrasion by sediment movement is probably more important than the effect of velocity alone. For example, Jowett and Biggs (1997) found that a five-fold increase in the flow of the Tongariro River resulted in the total removal of periphyton from artificial substrates, whereas in another river with less sediment movement, there was little change in the amount of periphyton on artificial substrates after a four-fold increase in flow. The amount of substrate that moves during a flood increases with flood magnitude and decreases with increasing substrate size, and thus so does the effect on the invertebrate community. Using marked substrates in tributaries of the Taieri River, Scarsbrook (1995) found that a four-fold increase in discharge resulted in the movement of 40% of marked particles in a small stream with an average bed particle size of 32 mm. In another stream with an average bed particle size of 70 mm, he found less than 20% movement for a four-fold increase in discharge.

Methods for the characterization of stream beds and calculation of the onset and amount of bed movement are essential for determining flow regime requirements for flushing flows and refinement of the relationships between stream biota and flow variability. Although the importance of substrate stability and flood frequency to stream biota in New Zealand rivers has been stressed (Biggs, 1995; Francoeur *et al.*, 1998), bed stability has been difficult to quantify. Nikora *et al.* (1998) described a method of characterizing stream bed roughness as a random three-dimensional field that showed clear structural differences between worked and unworked river gravels and produced measures of roughness potentially useful in studies of stream hydraulics and bed movement. Using more conventional hydraulic formulations, Duncan and Biggs (1998) suggested a bed stability formula that showed how bed stability could explain observed differences in stream periphyton and invertebrate communities not explained by the frequency of freshes (FRE_3) alone.

5 Decision-support system

Instream habitat surveys are time consuming, and a faster and cheaper method using at-a-station hydraulic geometry has been developed into a decision-support system, WAIORA (Kingsland and Collier, 1998). WAIORA uses simple models to predict the effect of an abstraction or point discharge on instream habitat, water temperature, dissolved oxygen and total ammonia. A simple field survey method was seen as the key to predicting basic hydraulic information for these models. The use of at-a-station hydraulic geometry relationships for instream habitat assessment was compared to depth and velocity predictions using habitat simulation techniques (IFIM) in two streams (Jowett, 1998). Hydraulic geometry relationships were determined from measurements of stream width and depth at five cross-sections at two calibration discharges. Cross-sections were located in 'runs', a habitat type intermediate between pools and riffles, and depth was measured at five points across each cross-section. The hydraulic geometry relationships predicted mean depth and velocity within 8% of reach average values determined from IFIM surveys in the calibration range and within 10–15% when extrapolated beyond the calibration range.

WAIORA allows water managers to assess quickly whether an application for a point discharge or abstraction is likely to have significant environmental consequences and whether more detailed studies are necessary. The steps in the decision process are to estimate natural low flows, assess the magnitude of the change on instream habitat, water temperature and water quality, and then to compare the environmental effect with guidelines to determine whether the change is sufficient to warrant more detailed consideration. A record of the assessment is stored in a database and can be used for reporting.

III Erosion, sediment transport and sediment yield

Recent research has shed considerable light on the processes and causal factors that account for regional variations in suspended sediment loads and lake sedimentation. A particularly important aspect is the explicit linkage of processes of sediment delivery from hillslopes and processes of sediment movement through the drainage system, to clarify the way in which vegetation, land use and storm characteristics can modify fluvial processes.

Regional-scale analyses of suspended sediment measurements in New Zealand rivers, which were published around 1980 (reviewed in Hicks and Griffiths, 1992), showed sediment yields spanning four orders of magnitude. Values ranged from 30 to 100 t/km^2/y in intermontane regions of the South Island, to 10 000–30 000 t/km^2/y in the central Southern Alps and the eroding mudstone hill country of the East Cape, North Island. The analyses explained the variability in sediment yield largely in terms of mean annual rainfall, with storm characteristics and catchment lithology as of lesser significance. Griffiths (1981) concluded that for 33 rivers in the South Island, specific annual suspended sediment yield G (t/km^2/y) could be estimated from catchment mean rainfall P (in metres) by the equation (with a coefficient of determination of 0.64):

$$G = 67.6\, P^{2.4}$$

An improvement in fit can be achieved by developing four regional equations (with coefficients of determination of 0.87–0.95), the regional differences being inferred to relate to rainfall frequency and intensity characteristics.

Recent research has added considerable detail to our understanding of the controls on regional erosion and sediment yield. Hicks *et al.* (1996) analysed suspended sediment gaugings to estimate sediment yields for 203 rural catchments, which were distributed throughout the country and had a wide range of climate, topography and vegetation cover. The results confirmed the importance of precipitation, but demonstrated also the effect of geology (Figure 3). Regression analysis for the catchments

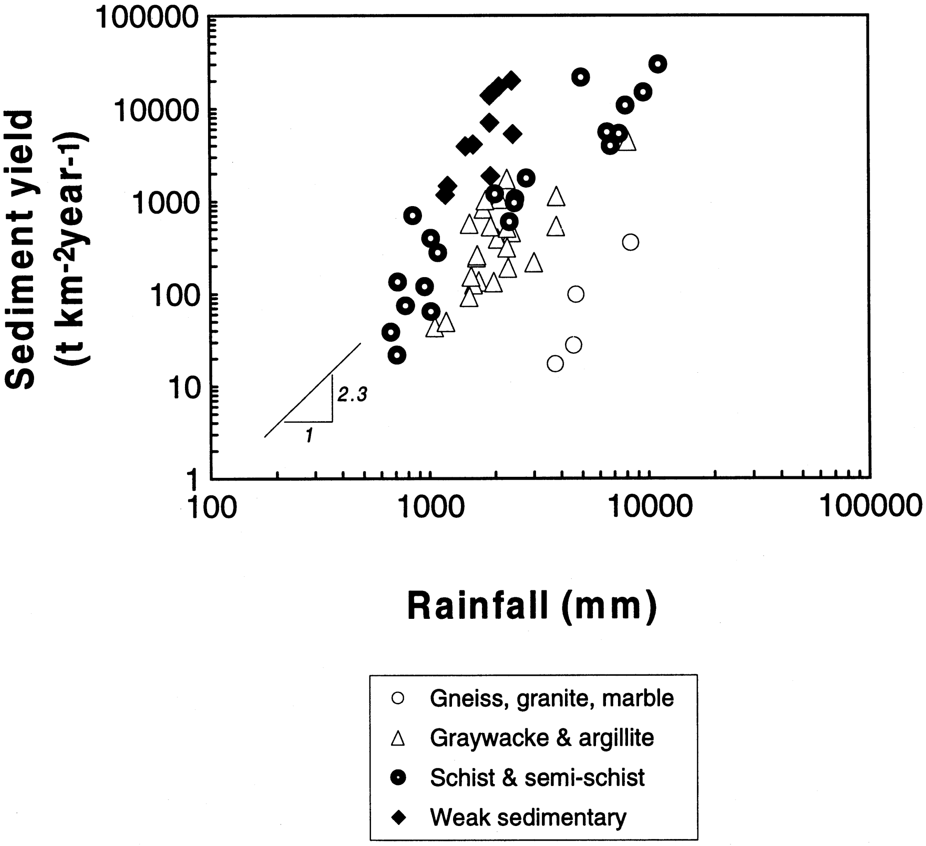


Figure 3 Sediment yield as a function of mean annual rainfall for New Zealand catchments with selected lithologies
Source: From Hicks *et al.*, 1996. Reproduced by kind permission of the International Association of Hydrological Sciences

grouped according to geology indicates relative sediment yields, for a given rainfall, in the ratios 1:15:25:900 for gneiss/granite/marble, greywacke/argillite, schist and soft marine sediments, respectively. The differences relate not just to lithology, but also to tectonic setting, since the highest yields tend to be from catchments located near the boundary between the Indian and Pacific plates. The influence of Quaternary history on contemporary sediment yields has received less attention, but Quaternary river terraces, outwash surfaces and alluvial fans provide sources of readily mobilized sediment to rivers in many parts of the country.

The advisability of supplementing fluvial suspended sediment measurements with other methods of estimating sediment yield has been neatly demonstrated by Pickrill's (1993) use of sedimentation data in Fiordland. Earlier work had concluded that sediment yields in this area of high rainfalls are also very high (> 10 000 t/km^2/y), but Pickrill concluded from seismic profiling and radiometric dating of sediment fills that long-term yields range between only 28 and 209 t/km^2/y. Recent research in the Tertiary mudstone catchments of the North Island, whose rivers carry particularly high sediment loads, has combined several different types of evidence to quantify sediment yields and explore the processes and controlling factors involved. A crucial control on sediment yields is the particular combination of hillslope erosion processes that deliver sediment to the channel. Hicks *et al*. (in press) applied a sediment-flow rating procedure to suspended sediment records for three sites in the Waipaoa River basin, to evaluate the differences between catchments in which the dominant sediment delivery processes are gullying (the Mangatu River subcatchment) and shallow landsliding (the Te Arai River subcatchment). The magnitude–frequency relation for event sediment yields in the Te Arai River (Figure 4) reflects the existence of a threshold for sediment supply, with relatively infrequent rainstorms providing periodic influxes of sediment from shallow landslides. Suspended sediment concentrations increase 50-fold following landsliding, and decline over the following two years, as material placed into temporary storage is remobilized. The magnitude–frequency relation for the Mangatu River indicates a readier, more consistent sediment supply to the river from gullying. Concentrations increase only two-fold after a large rainstorm, and decline over the following 2–3 years. The difference in sediment supply in the two catchments is indicated by the flow at which 50% of the sediment load is transported: 0.73 and 0.19 times the mean annual flood for the Te Arai and Mangatu Rivers, respectively. Overall, a greater proportion of the sediment yield is generated by extreme events in the Te Arai River.

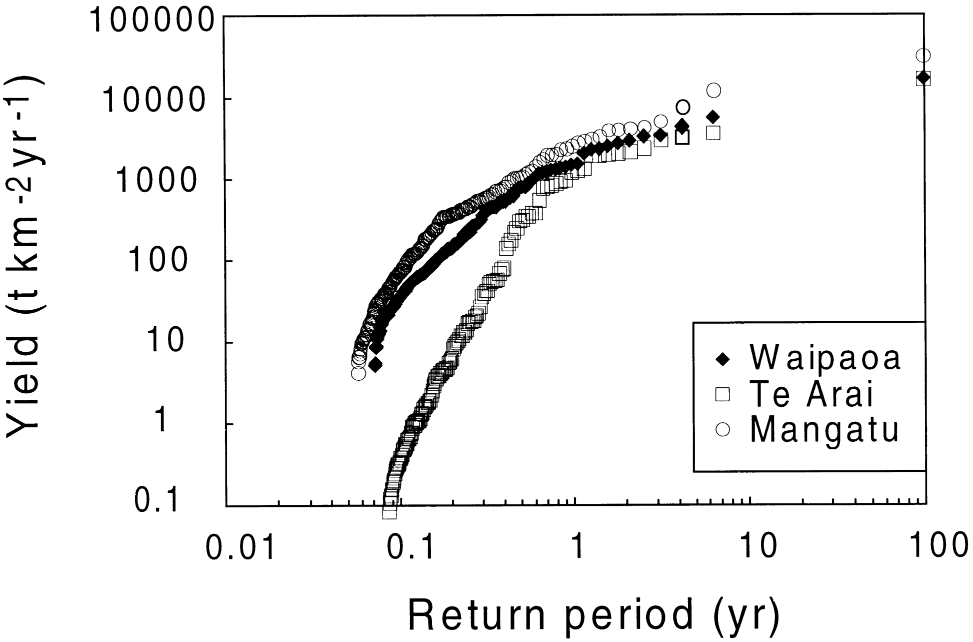


Figure 4 The magnitude–frequency relation for event sediment yields in the Te Arai River
Source: From Hicks *et al*., in press. Hicks, D.M., Gomez B. and Trustrum, N.A., *Water Resources Research*, copyright the American Geophysical Union

Landsliding generated an estimated 49% of the total 42 million tonnes of suspended sediment load carried by the Waipaoa River during Cyclone Bola in 1988 (Page *et al.*, in press). This storm had an annual exceedance interval of 1 in 100. In the most landslide-prone land system in the catchment, Te Arai, landslide density exceeded 3.2 slides/km^2, and sediment generation (estimated from field measurements of landslide extent and depth) averaged 421 m^3/ha. However, on a long-term basis landslides are estimated to contribute only 16% of the total load. There are three basic reasons for this: (1) gullying and bank erosion, which continually supply sediment directly to the drainage network, are dominant during lower magnitude, more frequent events; (2) a rainfall threshold of approximately 200 mm is required to initiate landsliding; and (2) about 50% of landslide debris is retained on the landscape. Landslides during Cyclone Bola contributed only approximately 1% of the expected sediment yield over a 100-year period, despite the impact of the storm on the landscape.

Cross-section surveys of dated terraces and channels in two tributaries of the Waipaoa, the Matakonekone Stream (430 ha) and Oil Springs Stream (305 ha), showed that 96×10^3 m^3 and 206×10^3 m^3 respectively of sediment was stored along the channels during Cyclone Bola in 1988 (Marutani *et al.*, in press). The surveys also showed that 12.5×10^3 m^3 per year and 8.3×10^3 m^3 per year respectively of stored sediment was subsequently removed during 1988–96. (In comparison, estimated volumes of sediment generated during 1960–88 were 47×10^3 m^3 and 106×10^3 m^3, respectively. Estimates used photogrammetric analysis of the dimensions of gullies, which were the principal source of sediment.) Marutani *et al.*, conclude that the two streams respond to large storms by instantaneously aggrading, and then gradually excavating the temporarily stored sediment.

In the nearby Tutira Catchment, landslide erosion accounted for 89% of the total 1.35 million m^3 sediment that was generated during Cyclone Bola (Table 1; Page *et al.*, 1994). The sediment loss represents a surface lowering of 42 mm during the event, or 83 mm on the moderately steep to steep hillsides which contributed more than half of the sediment, but comprise only 15% of the catchment area. However, only 6% was actually

Table 1 Sediment budget for the Tutira Catchment during Cyclone Bola

Budget component	Location	Process	Sediment flux	
			Volume (m^3)	%
Input	Hillslopes	Landsliding	1 200 000	89
		Sheet erosion	96 000	7
		Tunnel gullying	25 000	2
	Valley floors	Channel erosion	28 000	2
Total			1 349 000	
Storage	Hillslopes	Deposition	286 000	21
	Valley floors	Deposition	290 000	22
Total			576 000	
Output	Lake bed	Sedimentation	686 000	51
	Lake outlet	Stream transport	87 000	6
Total			773 000	

Source: From Page *et al.* (1994).

transported from the catchment during the storm, since 43% of the total was redeposited on lower hillslopes or floodplains, and 51% in Lake Tutira, at the catchment outlet.

Sediment cores in Lake Tutira display well defined pulses of sediment input during storms, particularly since the catchment was placed under pastoral land use in 1878 (Page and Trustrum, 1997). The thickness of sediment layers in the lake increases exponentially, relative to the storm rainfalls which mobilized the sediment, above a threshold of around 200 mm of rainfall. This indicates that high-magnitude events supply disproportionately large amounts of sediment to the drainage system (Trustrum *et al.*, in press). However, comparison of the lake sedimentation and precipitation records shows that factors other than storm rainfall also modify sediment loads. These include the previous exhaustion of readily eroded sediment sources and the time available for subsequent recovery, variations in storm characteristics and antecedent conditions, and a tendency for event sediment delivery ratio to increase with increasing storm magnitude.

On the geological timescale, sedimentation rates have varied markedly since Lake Tutira was created by a landslide *c.* 6500 y BP. Comparison of the sedimentation record with palaeoclimatic evidence indicates that clusters of sediment pulses were associated with increased storm frequency during La Niña phases of the El Niño-Southern Oscillation (Eden and Page, 1998). Sedimentation rates approximately doubled, with a five-fold increase in storm frequency.

Before human settlement, with a forest cover in the catchment, the sedimentation rate in Lake Tutira was 1.47 mm/y. Sedimentation rate increased to 2.43 mm/y following conversion by fire of the forest cover to bracken fern by Polynesian settlers after 560 BP. Since European settlement, sedimentation in the lake has increased to 13.0 mm/y, at which rate the lake will be infilled within 600 years. Sedimentation has been accelerated by the increased extent and frequency of landsliding, the extension of the channel network on to hillslopes and into swales, and remobilization by channelization and drainage of sediment formerly stored in valley fills and floodplains.

Inherent variations in river sediment loads, which are due to differences in climate, geology and storm characteristics, provide a context within which management interventions can be designed. Differences in sediment load due to land use and vegetation cover have been recognized (though not necessarily quantified) for many years in New Zealand, and have provided the basis for extensive catchment and river control works, using vegetative methods. The recent research summarized above provides many pointers for more specifically targeted catchment management. Variations in sediment load are attributable to differences in topography, land system type, the relative importance of sediment delivery processes (landsliding, gullying, etc.), their locations with respect to the channel system, the pathways whereby sediment travels from hillsides into the channel system, and the ability of watercourses to remobilize sediment that has been placed into temporary storage in terraces, floodplains and other deposits. The ability to pinpoint the locations within a catchment-channel system which are likely to be the sources of the greatest volumes of sediment enables the manager to apply control methods with maximum effect.

IV Channel networks and hydraulic geometry relations

New Zealand scientists have made a limited contribution to the literature on channel networks and downstream hydraulic geometry. A notable exception was the work of Griffiths (1980), which compared data for six gravel-bedded rivers with a semi-theoretical analysis and the results from investigations in other countries to establish a justification for then current practice in stable channel design.

More recently, a major contribution to network analysis has been made by several catchment-wide data collection exercises, in which channel properties and discharge have been measured under constant flow conditions at up to 336 sites in each catchment (Ibbitt *et al*., 1998; McKerchar *et al*., 1998; Henderson *et al*., in press). The exercises were planned to enable investigation of the optimal channel network (OCN) concept (Rodriguez-Iturbe *et al*., 1992), and have served to clarify its constraints (Ibbitt, 1997). (An OCN minimizes the overall energy expenditure within an equilibrium channel network.)

The width exponents *b* for four of the five individual rivers, and for those rivers aggregated by Griffiths (1980) and by Jowett (1998), agree approximately with that predicted by the OCN model (Table 2). However, for velocity, depth and slope, the OCN model does not well predict the exponents, and Griffiths' (1980) analysis overall is not inferior to the OCN model. Jowett (1998) suggests that the variations in depth and velocity exponents between studies may be explained by differences in the gradients of the streams included in each; his own study indicated that gradient explained 6–11% of the unaccounted variance in relationships between discharge and depth and velocity.

Suggested explanations for the failure of the OCN model to match the field observations include, in addition to those associated with sampling and measurement difficulties:

- Unequal erodibility of channel bed and banks, indicated for example by the presence of small gorges in tributary catchments of the Taieri.
- Nonuniform specific discharges (in the Cropp Catchment).
- Variations in lithology and topographic steepness between and within catchments.
- A failure of many catchments in New Zealand to achieve dynamic equilibrium, because of the active tectonic environment at the edge of the Pacific plate, and uplift rates of up to 6 mm/y.

The widespread presence of Pleistocene and Holocene fluvioglacial terraces and other deposits, and the frequent occurrence of waterfalls and bedrock outcrops in channel bed and banks, indicate the strong influence on channel morphology of the geological setting and history of New Zealand. In other words, New Zealand river networks cannot be regarded necessarily as time-independent equilibrium networks. Even the Taieri catchment, which is in one of the country's oldest landscapes, is not well modelled by the OCN concept.

Further work on the Ashley River (Ibbitt *et al*., in press) has explored the effect on network properties of the geological and tectonic setting of the catchment. A particular feature of the Ashley Catchment is nonuniform tectonic uplift, with mountain ranges rising at rates of up to about 3 mm/y along the catchment perimeter, and a central zone of uplift which is reflected in a major drainage divide along the axis of the catchment.

Table 2 Downstream hydraulic geometry exponents for selected New Zealand rivers

	Ashley[1]	Taieri[1]	Cropp[2]	Hutt[1,4]	Buller[1,4]	Aggregated NZ gravel rivers[3,4]	Selected NZ rivers[5]	'Traditional' values[3]	OCN values[1]	Griffiths' analysis[3]
m (velocity)	0.318	0.236	0.22	0.34	0.10	0.11	0.24	0.1	0.0	0.11
b (width)	0.440	0.517	0.47	0.52	0.39	0.48	0.49	0.5	0.5	0.44
f (depth)	0.242	0.247	0.31	0.14	0.51	0.43	0.24	0.4	0.5	0.44
z (slope)	–0.317	–0.314				–0.49		–0.5	–0.5	–0.44
Sample size	336	300	47	7	8	6 rivers, 25 sites	73			

Notes
1) From Ibbitt (1997).
2) From Henderson *et al.* (in press).
3) From Griffiths (1980).
4) Data are for gauging sites, at which the channel is likely to be more uniform than average.
5) From Jowett (1998).

A set of network simulations using the energy-based OCN procedure and the physically based SIBERIA model (Willgoose *et al*., 1991), was compared in terms of the hypsometric curve and integral energy expenditure, catchment width and convergence. It was concluded that the simulation which most closely matched the actual channel network statistics was provided by the SIBERIA model which incorporated a realistic tectonic history of the catchment.

V Gravel-bedded and braided-river processes and morphology

New Zealand's gravel-bedded rivers, particularly the large braided rivers of the South Island, have been a fruitful source of research for many years. There have been several strands of applied research, including the development of procedures for stable channel design and management, estimation of bedload transport for management of aggradation and commercial gravel extraction, and evaluation of channel morphology from the perspective of instream – particularly recreational boating and fishery – uses.

The large New Zealand braided rivers, up to 2 km wide in the case of the Rakaia River, present huge challenges for the scientist. Interpretation of historical maps and aerial photographs, combined with field examination of terraces and bars of different ages, provide a mesoscale context in which to place studies of present-day processes (Carson, 1984; Warburton *et al*., 1993). A number of studies has demonstrated that, for all their unstable appearance, large areas of the beds of braided rivers may remain essentially unchanged for years or decades, depending on the sequence of flood events that is experienced and their ability to rework sediment that has been placed into storage (Hoey, 1994). At the same time, relatively minor changes in bed contours at critical points, particularly at flow divergences, and in the shares of flow directed down diverging anabranches, can cause widespread changes to channel pattern and morphology further downstream (Warburton *et al*., 1993).

A number of early studies used large field teams to make sufficient measurements to characterize hydraulic geometry and instream habitat in several rivers at multiple flows (Mosley, 1983; Mosley and Jowett, 1985). There are inherent limitations to this approach, apart from cost, particularly the limited ability to go much beyond simple description of a river. Measurements of bedload are needed to advance our understanding of how bars and anabranches change and migrate, but these are perhaps the most time-consuming and inaccurate measurements of all (Davoren and Mosley, 1986). A combination of repeated cross-section surveys, aerial photograph interpretation, bedload measurement and bedload tracing was used to compare processes of channel change in a braided and a straight reach of the North Ashburton River, the latter subject to intensive management (Laronne and Duncan, 1992). The braided reach was found to be more stable during small events, with sediment transport principally along the established anabranches (Figure 5a). In the straight reach, however, bedload transport paths were subparallel to the existing channel, gravel was able to move across bar surfaces, and new bars and channels formed rapidly in response to the migration of gravel sheets and lobes (Figure 5b). In a larger event, approximately equal to a mean annual flood, both reaches experienced extensive sediment transport, reworking of bars and channel reformation.

The case of the North Ashburton River is particularly interesting because it provides

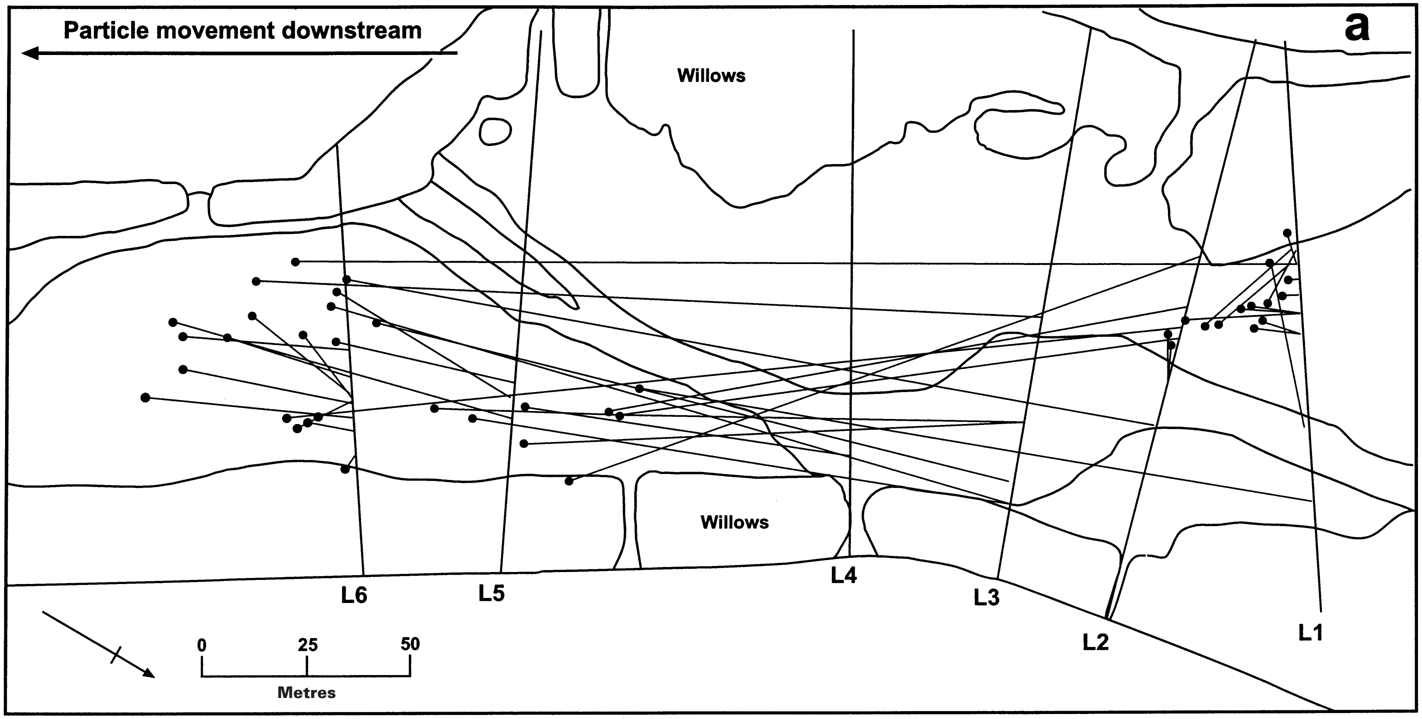
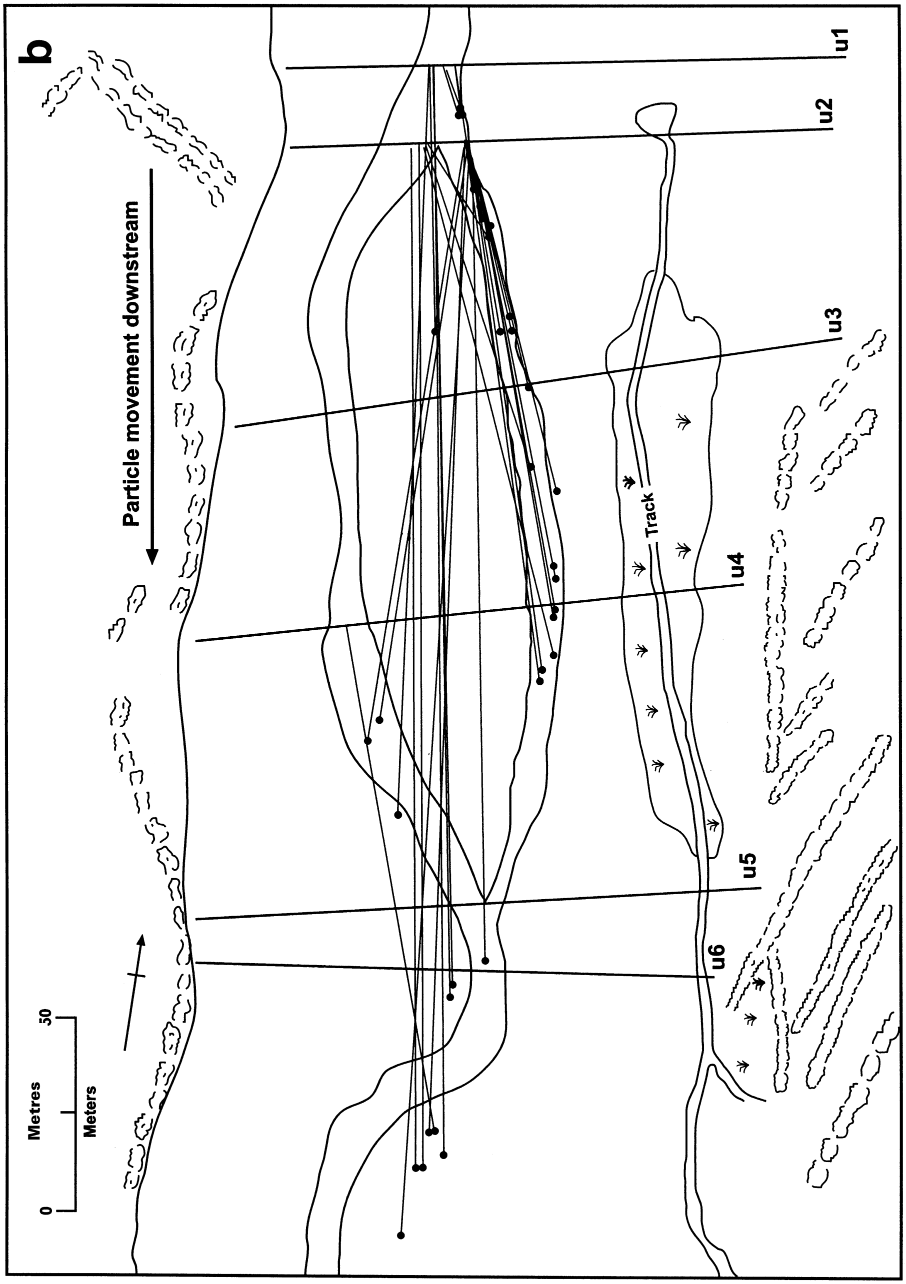


Figure 5 Displacement of tracer pebbles in the North Ashburton River during a 31 m^3/s discharge: (a) in the braided reach; (b) in the confined reach
Source: From Laronne and Duncan, 1992. Bedload transport paths and gravel bar formation. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*. Copyright © John Wiley & Sons Limited. Reproduced with permission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an example where standard New Zealand river engineering practice, to control channel instability and aggradation by confining the channel with flood banks, groynes, and vegetative bank protection (Nevins, 1969), has not been successful. The field observations reported by Laronne and Duncan (1992) indicated that constriction has increased the frequency of sediment transport in the confined reach, but aggradation nevertheless has continued. In one of a series of hydraulic model studies carried out at Lincoln University over a period of 20 years, Davies and Lee (1988) shed light on the possible reasons. They concluded that reducing the width of a model braided stream increases sediment transport capacity, at least until the ratio confined/unconfined width reached 0.35. However, they also concluded that any change in the rate of aggradation (i.e., the difference between sediment input and output) depends on sediment input. If sediment input is greater than 2.3 times the transport capacity of the unconfined equilibrium channel, then aggradation rate is *increased*. Noting the difficulty of establishing both the sediment input and the equilibrium transport capacity, Davies and Lee (1988: 125) concluded that 'in any river in which aggradation needs to be controlled, confinement is unsuitable as a control technique because the rate of sediment input will be high; conversely, where the sediment input rate is low enough for confinement to be beneficial, aggradation usually will not be a severe problem'.

While Davies and Lee were exploring experimentally the influence of channel width on bedload transport and aggradation, Carson and Griffiths (1987) were applying an analytical approach to the same issue. Their analysis focused on the attributes of the MTC (maximum transport capacity) channel, using earlier analyses of sediment transport, channel roughness and stable channel shape. They argued for the existence of an optimum channel width for a given flow and sediment input, on the basis of a balance between the width of the zone of moving bedload and the bedload transport per unit width of that zone. Their discussion placed particular emphasis on the effect on bedload transport of fluctuating discharge, a particular characteristic of New Zealand braided rivers. They drew attention to the implication of measurements in the Ohau River, over a flow range of 25–500 m^3/s, that increasing discharge is accommodated principally by the addition of deeper, faster water (with a constant width of shallow, slow water) (Mosley, 1982). As a result, the area of riverbed across which sediment is transported and the transport rate both increase progressively (since bankfull discharge in a braided river appears to have a recurrence interval far higher than the mean annual flood, at least in New Zealand rivers). Carson and Griffiths (1987: 107) comment that 'the hypothesis must not be overlooked that the braided channel is the efficient form for transporting large loads of sediment'.

On the other hand, the observations by Davoren and Mosley (1986) of bedload movement in the Ohau River indicate that, even at high and infrequent flows, sediment transport in a downstream direction is not continuous, because individual particles tend to move from scour zone to deposition zone – a matter of a few tens or hundreds of metres in the Ohau (cf. Carson and Griffiths, 1989). Hence, sediment transport for the river as a whole is accomplished by a large number of disconnected zones of moving sediment, associated with those areas of flowing water with depth and velocity sufficient to entrain and move bed material (termed 'jet zones' by Thompson, 1985). A complete understanding of channel changes in braided rivers therefore requires both temporal and spatial variations of sediment transport to be considered.

The potential applications of hydraulic model studies to understanding and managing braided-river behaviour and morphology recently have been reviewed in a special issue of the *Journal of Hydrology (New Zealand)* (Vol. 35, no. 2). In a concluding article, Warburton *et al*. (1996) identified areas of particular research potential, including the effects of model distortion on sediment transport and channel morphology, model verification procedures and calibration of models against the prototype. Davies and Lee (1988) had pointed out that hydraulic model data can be scaled up to the prototype only if the degree of geometric similarity between model and prototype can be assessed, but that the greatest obstacle is a lack of prototype data, especially on sediment transport capacity.

Substantial effort has been directed recently into developing technologies which do not have the limitations of the methods used in earlier field studies. Digital elevation models have been confirmed to be greatly superior to the 'traditional' cross-sections, as a basis for numerical modelling. They can be prepared more cost-effectively, using a combination of data from digital photogrammetry for exposed riverbed, echo sounding/global positioning system (GPS) surveys for deep submerged riverbed, total station/GPS surveys of the water's edge and shallow submerged riverbed and conventional stereoscopy to fill gaps in coverage by the other three methods (Duncan and Carter, 1996; Carter and Shankar, 1997). Two-dimensional hydraulic modelling of a braided river has been found to be feasible (Figure 6; Duncan and Carter, 1996), in parallel with similar work in other countries. Similarly, work is presently proceeding in New Zealand, in co-operation with scientists from overseas, to model sediment transport and resulting bed-level changes.

Recent international developments in the technology available to river scientists offer tremendous scope for future research. It appears that a combination of physical-scale modelling, two-dimensional numerical modelling, remote sensing of the prototype and on-the-ground field observation promises progress which no one of the approaches alone can achieve. Field observations are essential to calibrate numerical models and establish similarity relations for physical models, and to verify both. Perhaps more importantly, they provide the scientist with a 'reality check' that may not be provided by even careful scrutiny of laboratory models, remotely sensed images or computer outputs.

VI Current research directions

Current research programmes in the area of river morphology and management, predominantly funded from the Public Good Science Fund, address three main areas.

Gravel-bed river mechanics, including:

- Flow turbulence and its relationship with bed disturbance, sediment transport and flow resistance.
- The rate, spatial variation and scaling of morphologic change, sediment transport and bank erosion in braided channels.
- The effect on the above of external changes in flow regime and sediment supply as a result of natural (e.g., climate change) or human-induced (e.g., hydrogeneration) effects.

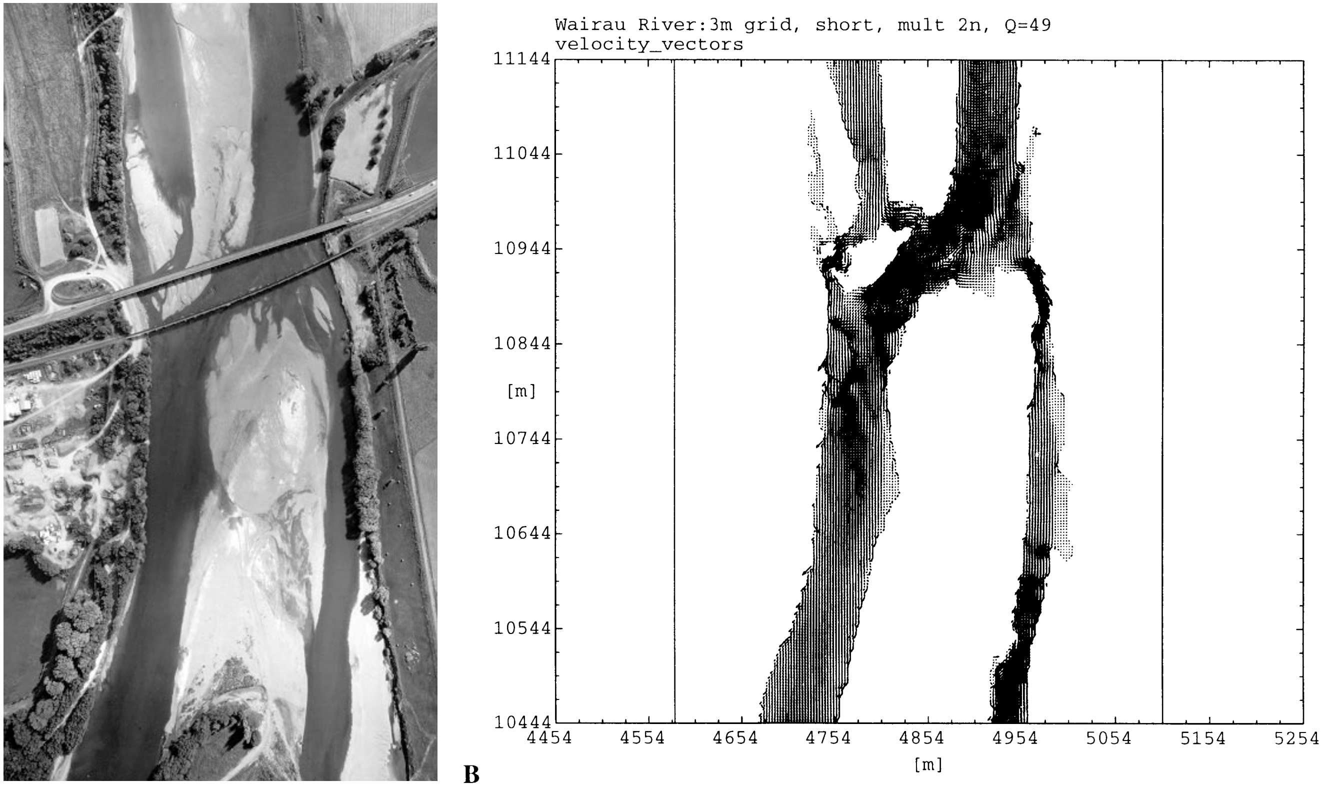

Figure 6 The braided Wairau River at Tuamarina: (a) an aerial photograph with a rated flow of 49 m^3/s; (b) Velocity vector plot of the 2D model output
Source: From Duncan and Carter, 1996. Reproduced by kind permission of the New Zealand Hydrological Society

Climatic and tectonic controls on landscape evolution, including:

- Geomorphic analysis of sediment generation, storage and delivery.
- Development of sedimentation histories and tectonic uplift rates using terrestrial and offshore sediment cores, to link in-river processes with processes on the land surface and in the ocean offshore.
- Creation of a model of landscape evolution to examine future landscape change under differing environmental and land-use scenarios.

Instream habitat hydraulics, river ecosystems and interactions with riparian land use, including the development of:

- models to predict the effects of changes in river channel structure and flow on instream biodiversity; and
- techniques for stream restoration, riparian zone management and sustainable catchment land use.

In addition, there are a variety of other projects which are on a smaller scale or have components relating to river morphology. These include, for example, investigation of lahar deposits along the Whangaehu River, down which flow lahars from the crater of volcanic Mount Ruapehu. Descriptions of the major river-related research programmes can be located on the websites maintained by the Foundation for Research Science and Technology (http://www.frst.govt.nz/), and by the two Crown Research institutes principally engaged in river-related research (http://www.niwa.cri.nz/ and http://www.landcare.cri.nz).

Increasingly, river research in New Zealand is multidisciplinary in nature. Earlier sections have noted how linkages with, for example, tectonics, fish biology and fluid dynamics, have enabled river specialists to understand better their subject-matter and make their findings more useful. The need to place rivers in the context of the landscape and of human activity is perhaps even more obvious than in the days of large-scale soil conservation and catchment/river control schemes. A good example is provided by a recent study of the aggrading, proglacial Waiho River, in which Davies (1997) noted that several earlier studies of the river had failed to provide accurate predictions of its behaviour. He suggested (p. 136) that ‘a comprehensive interdisciplinary investigation of the meteorological and tectonic inputs to, and sediment outputs from, the Waiho system would provide a much better background’ for river and infrastructure management on its alluvial fan. Further, Davies (1997: 143) suggested that ‘if a future catastrophe is to be avoided, the behaviour of the human system must adapt to the behaviour of the natural system rather than vice versa; existing facilities must be moved out of harm’s way.’ He concluded that strategies would need to be informed by continuous monitoring of the natural system and by continued attempts to improve understanding of its behaviour.

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