TECHNICAL PAPER

RIVER NATURAL CHARACTER

NATURAL CHARACTER GUIDELINES FOR THE MANAGEMENT OF GRAVEL-BED RIVERS IN NEW ZEALAND

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1 INTRODUCTION

1.1 CONTEXT

Rivers and their wider waterway networks are dynamic and responsive systems, influenced by both physical and biological processes. As open energy-exchanging systems they continually respond to changes in both local and wider catchment conditions. The character of any river reach thus reflects the processes taking place along it, which move water, sediments and woody debris, and the wider catchment influences from the connectivity of these processes.

Rivers are an integral part of the hydrological cycle, collecting the water that falls on the land and carrying it to the sea, along with nutrients and sediments. Rivers both divide and integrate the landscape, taking water from the land and releasing it back onto floodplains and into groundwater, thereby generating a range of natural margins and boundaries in the landscape. Rivers both form and are formed by the wider landscape, and their character depends on the nature and intensity of the influencing forces of climate and catchment setting.

The effectiveness of any management of rivers can be enhanced by an understanding of the larger patterns of watershed processes, recognising the diversity of river types and reach character, and the changes that take place over time due to the variability of the influencing forces.

This paper outlines an approach to river management based on the natural character of gravel-bed river reaches and the different channel forms and response dynamics of river reaches. The approach has been developed for active gravel-bed rivers in New Zealand [NZ]. It is framed by the nature of the New Zealand environment, while recognising the human modifications and disturbances arising from the historical development practices and past management regimes used in New Zealand.

In this approach to river management, an active channel area is defined for a given reach, based on the river type and the nature and rate of channel changes over time. This active channel area provides space for the interactive processes of moving water, sediments and debris/organic matter. Along the edges, a vegetation buffer zone provides a diffuse and flexible boundary that assists in the containment of this activity. The active channel, vegetation buffer zones and additional reserve areas give rise to a defined river corridor, which is the area set aside for the river.

The width and alignment of the active channel area are determined from empirical relationships and the local character of a river reach. This then gives a channel area that is based on the channel form of the reach, with its particular pattern and rate of adjustment over time. River survey data and repeat aerial photography, along with early survey plans of river beds, are used to determine the river type and channel variability. Then theory and field based relationships are used to determine a width that suits the reach type, given the catchment and climatic setting.

The width of the buffer zones is based on potential erosion embayments, which is linked to the size and patterns of the channel forms along the reach. The design channel areas and

vegetation buffers do not, though, have fixed boundaries. The design allows for the management of moving edges, with the interface between the active channel and edge vegetation being a movable boundary. The drawn lines of any design are, then, guidelines developed for the prevailing conditions and alignment, and they may not suit historical or ancestral conditions. The aim is to provide space for the river processes, thereby minimising management interventions by allowing river activity to come and go within the channel area and its margin vegetation.

The design philosophy is one of flexibility and adaptive response. It recognises that catchment processes and boundary conditions change over time, and this changes river behaviour and the space occupied by the active channel areas.

If reach conditions change significantly, for instance, due to a large flood event or cyclical change in flood intensity, a pulse of bed material sediments passing through the reach, or the spread of vegetation across the active channel area, then the design channel area and management approach may have to change in response. The drawn boundaries defining the interface between the active channel area and vegetation buffers are based on medium term (decadal) averages, derived from the current dynamics of channel movement and the shifting back and forth over time of channels that this dynamic gives rise to. If there is a significant alteration to the channel dynamics then the design boundaries must be reviewed in the light of the changed conditions. The outer boundary of the river corridor is, though, a more fixed boundary, with the aim of separating the assets and activities of people from the habitats and activities of the river.

Effective river management requires ongoing maintenance and remedial measures after flood events, whatever the river conditions or defined channel and buffer zone areas. The approach outlined here includes management interventions and reestablishment works in respond to changes in channel form and alignment, varying sediment fluxes and the spread or removal of vegetation. However, in contrast with other approaches, it neither imposes a fixed edge to the active river channel, nor does it leave the river channel completely alone. It involves an intermediate degree of management, with the long term aim of minimising the economic costs of both river management and damage or loss of land and infrastructure assets, while maintaining a diverse and ecologically productive river environment.

The paper outlines the development and application of this management approach to river reaches of different types and character, along gravel-bed rivers throughout New Zealand.

The paper is structured as follows. It begins with a brief overview of the New Zealand environment, followed by historical management practices since European colonisation of Aotearoa/New Zealand. This is the context in which the approach was developed, and outlines the understanding of the NZ landscape and climate that underlay the development of an alternative approach to river management, relative to historical practices. The general principles that guide the assessment of natural character and the form of river reaches are then outlined, prior to documenting the methodology itself. The management principles that arise from this approach are discussed, as well as implementation options and constraints. Finally, examples are given of the application of the management approach, mostly on rivers flowing from the main axial mountain ranges of the NZ landmass.

Before outlining the approach and its design philosophy and methodology, however, a brief summary is given of the development of the approach, to give an historical context and the reasoning behind its genesis.

1.2 DEVELOPMENT OF THE RIVER MANAGEMENT APPROACH

The approach was first developed, in its fully applied form, based on both catchment and reach studies, for the gravel-bed rivers of the Ruataniwha Plains in central Hawke's Bay. The investigation studies and river management proposals were part of a comprehensive review of the "Upper Tukituki Catchment Control Scheme", carried out in the mid 1980s, for the Hawke's Bay Catchment & Regional Water Board.[18]

The original "Upper Tukituki" scheme was implemented in the 1950s and 1960s. The river channels had become congested with willows, and the main works involved the clearing of willows, gorse and lupin vegetation, the establishment of protective vegetation belts along the channel margins, and the construction of flood retaining stopbanks. Medium-sized flood events in the 1970s highlighted the channel aggradation that was occurring along the plains reaches, given the high bed material input from the headwaters in the Ruahine Ranges. The extraction of gravel from the river channels and raising of the stopbanks was proposed in response, along with further edge planting and vegetation strengthening works. For a number of reasons a revised scheme did not proceed, but a primary concern was the high input of sediment from the headwaters and the deposition of this material that was continuing to occur along the rivers crossing the Ruataniwha Plains.

The management approach that came out of the review investigations was influenced, and enabled, by two developments. First, the availability of accurate plan-form aerial photography, with repeated photographic runs taken at intervals over a period of decades. The first comprehensive vertical aerial photography of New Zealand was taken during World War II in the 1940s. By the 1980s repeated coverage at intervals of around 5 years was available, including accurate ortho-rectified aerial photographic plans. This provided a reliable information base to assess channel form and river adjustments over time, giving a clear and accurate picture of river channels, showing their form and extent of vegetation, and importantly, the rate of change of channel features and vegetation. The aerial plans also provided a very useful and informative base plan for the drawing up of design channels and edge zones of protection vegetation.

Second, research investigations and theoretical developments about channel form and sediment transport processes undertaken from the 1950s to the 1970s transformed the understanding of river dynamics and geomorphic processes. The 1980s investigations drew on this improving understanding, and in particular on studies concerning channel widths and form undertaken around the world, and especially on gravel-bed rivers of the Rocky Mountain ranges in Canada and the USA, and the Caucasus Mountains of the then USSR.[5, 6, 10, 13, 14]

Related studies on sediment transport processes and channel form had also been undertaken in New Zealand. Applying the differing theoretical frameworks and empirical formulae to NZ rivers in the context of the NZ environment was essential for effective management practices on the types and character of NZ river reaches.[4, 7, 8]

The examples attached to this paper include two reaches on the Ruataniwha plains, one on the Tukituki River and one on the Waipawa River. The aerial maps show the original design of the 1980s investigations, which has guided river management on these rivers since that time.

Asset management plans have also provided guidelines on the maintenance of the vegetation buffers, as flexible and erosion absorbing margins, with different responses as more of the vegetation is eroded away.

A range of alternatives, from a narrow closely managed channel to a wide corridor where the river can move and adjust with minimal interventions, was considered when developing a management alternative for the Ruataniwha Plains rivers. Then in the late

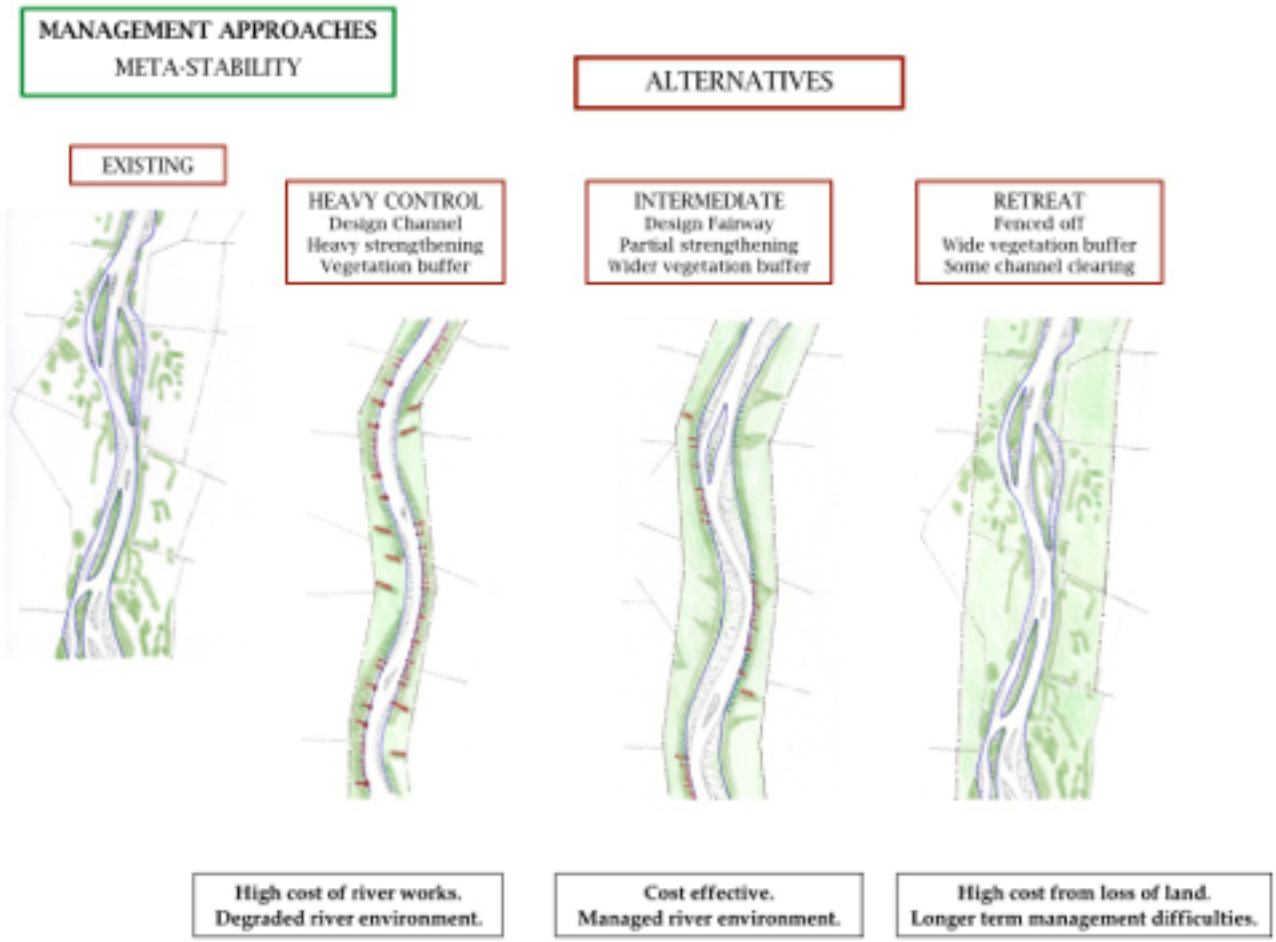
1980s, an economic and environmental assessment of these different river management approaches was carried out for reaches of the gravel-bed rivers of the Wairarapa Valley. General alternatives were considered for reaches of the Ruamahanga, Waingawa and Waiohine rivers, and later the Tauherenikau River.[21] This was undertaken as part of a reassessment of river management and a review of options, because of the withdrawal of central government from the management of watersheds and rivers, and their natural hazards, and the loss of government subsidies for catchment and river management schemes.

A diagrammatic representation of the main alternatives considered in these studies, and used for community consultation and explanations of the alternatives, is given in Figure 1. The studies showed that the approach with a defined active channel area within wide vegetation buffers that allow channel migration and a give-and-take at the channel edges, would be the most cost effective in the longer term, while maintaining an environmentally diverse river corridor. This approach was seen as an intermediate alternative, between a heavy control that fixed the channel edge, and a retreat that provided a wide river corridor, but one that would become densely vegetated. The main problem with a wider set back and minimal intervention option was that recently introduced (non-native) species would rapidly colonise the space and choke flood flows. Not only would the willows introduced by past vegetation management spread, but also self-seeding gorse, broom, tree lucerne and other invasive pioneers would colonise the river corridor. In time there would be breakouts from this enlarged area because of the deflection effects of the vegetation, and anabranching of channels through the vegetation.[21]

Essentially, the approach involves a systemic balancing of: on the one hand, the human occupation of floodplain land, with the risks of flooding, land loss and damage to assets this entails; and on the other, the space required by rivers for the natural processes that transport water, sediments, debris and nutrients, given the impacts that introduced vegetation is having on these processes.

Figure 1

RIVER MANAGEMENT ALTERNATIVES — Evaluation



2 RIVER MANAGEMENT

2.1 NEW ZEALAND ENVIRONMENT

New Zealand is made up of large islands on the tectonic boundary of the Pacific "ring of fire", where a segment of continental crust has been pushed and shoved, raised and sunk, over long periods of geological time. It has a mountainous backbone along the line of this boundary, with rapidly uplifted and shattered base rocks, and steep gravel-bearing rivers that have a short run from the mountains to the sea. It has a southern mid-latitude oceanic location, where the mountain ranges cut across the westerly circulation of anti-cyclones and depressions of these latitudes, giving rise to high intensity rainfalls.

Flood flows are generated very rapidly, and give rise to sudden but brief flooding of floodplains, under natural conditions. The relatively high flood flows and steep grade of rivers in New Zealand give rise to powerful highly turbulent flows that move large amounts of sediments and debris over short periods of time. However, the short duration of these floods suddenly truncates sediment transport and channel movement, and this can leave sharp hook embayments and other channel distortions in the river bed following flood events. The steep landscape of weak fault-broken and weathered base rocks gives rise to high catchment input of sediments, even with the natural forest cover of New Zealand. As a result, the alluvial (self-forming) channels of these rivers are highly mobile and change rapidly, even over human life spans.

The oceanic climate is highly variable, with an unstable seasonal pattern, and longer term variations from the oscillations of large global circulations, southern ocean circulations (around Antarctica) and circulations around the South Pacific. The diverse landscape and climatic regions of New Zealand are affected at different times and in different ways through the pulsating dynamic of these natural oscillations. The back and forth movement of a convergence zone of two large circulations in the Pacific Ocean gives rise to decadal long variations in the New Zealand climate. This Interdecadal Pacific Oscillation [IPO] is a major driver of regional variations in storm intensity and flood flows. Thus, in a given region, there are periods of high flood intensity followed by a generally quiescent period, before a return to more and larger floods. The river systems respond to these changes, and this is reflected in changes in channel form and vegetation extent within and along river channels.

During the last glacial age, NZ was mostly covered by open grasslands and scrublands, with forests on the margins and ice-fields along the higher mountain ranges. From around 15,000 years ago, there was a progressive covering and diversifying of forests, with the warmer climate and greater rainfall of the present inter-glacial period.

The isolation of NZ gave rise to unique and highly diversified temperate climate rainforests, with its own soil life and a fauna based on highly speciated birds, lizards and snails, and grasslands with a profusion of small flowering plants. The geological submergence of NZ meant that mammals had been eliminated from the ecology. Lowland podocarp forests, in particular, are highly diversified, as multi-layered forests with a complex mosaic of species and interactions between plant and soil life. These NZ forests have adapted to a high energy regime, with intense rain and strong winds, on steep erodible land, and have high resilience to climatic extremes.

The tectonic location of NZ, with its earthquake, volcanic and land uplift and subduction activity, has given rise to a very active landscape, with steep and fractured mountain ranges and fast-flowing and very mobile rivers. Its oceanic location gives rise to a highly variable climate, and its mid-latitude position means that global climate changes have a very pronounced effect on the climate.[9, 16, 17]

2.2 NEW ZEALAND RIVER MANAGEMENT

Significant habitation by people, which affected the environment, is very recent in Aotearoa/New Zealand. Polynesian migrations less than 1000 years ago brought the cultivation of sub-tropical vegetables, and the use of fire for cultivation, clearing and hunting. The hunting of large ground birds and the use of fire, along with climate changes, led to the conversion of large areas of forest to grassland, especially in the South Island, and the extinction of many large birds, including all of the flightless moa. The introduction of rats and dogs also led to the extermination of many small birds and invertebrates.

In the last 200 years, European exploration and settlement has had a much larger effect, especially in the North Island, and given rise to a very mixed up ecology, from introduced species and altered ecosystems. There has been the introduction, both by association and deliberately, of a vast array of plants and animals from all around the world, including grazing and predator mammals, game birds, freshwater fish, insects and many viral, bacterial and fungal organisms. At the same time, the large lowland and coastal wetlands were drained for farming use, with over 90% of all wetland areas being drained. Most of the lowland forests have been cut and burnt for pastoral farming, including steep hill country, with forest cutting for timber taking place up into steep range land.[1, 9, 16]

Apart from the remaining native forests on the steep mountain and range land of the main axial ranges of NZ and some volcanic mountains, the environment has been highly modified by human activities, most significantly by pastoral agriculture. Many invasive

species of plants have been introduced, and introduced mammals, both domestic and wild, have profoundly altered ecological relationships, and the health of present ecosystems.

Alongside the large-scale impacts on catchment vegetation and erosion processes, there have been a whole host of direct and intentional interventions in waterways and river systems. Many of these interventions have been to use land and water as economic resources, and then to protect productive assets from flooding and erosion.

Rivers and waterways have been confined and their movement restrained for flood and erosion mitigation purposes, as well as being modified or dammed for hydro-electric power, despite the high energy regime and sediment transport loads of most NZ rivers. At the same time, the introduction of invasive species that rapidly colonise waterways has profoundly altered the riparian vegetation and vegetative regime of rivers where the native forest cover has been removed.

The lower reaches of most rivers in NZ, including nearly all the larger rivers, are managed, and there are many flood and erosion mitigation schemes throughout NZ. The main aim of many of these schemes was the protection or development of agricultural land.

This, combined with a generally localised urbanisation along rivers and low population density, has meant that river management has been carried out using relatively inexpensive low strength methods. There has been a general reliance on vegetation alongside the river channel, and willows, in particular, have been used to manage bank erosion. Infertile varieties of willows have been used, but willows grow rapidly from cuttings, and snagged material can quickly spread willow vegetation across river channels.

Willows have been planted along waterways from the early days of European colonisation, and many waterways have become choked with willows due to their rapid growth and spread in the NZ environment. The use of willows for river management, while widespread, is very much a two-edged sword, and a periodic alternation between the clearing of willows from channels and the planting of willows along banks is not uncommon.[1]

Rivers are dynamic systems with continual losses and regrowth of vegetation in and along their margins. Besides willows, many other rapidly colonising species that have been introduced, including gorse, broom, lupin, tree lucerne and a range of acacia species from Australia. These introduced species have established and spread rapidly along NZ waterways. This has changed the vegetative makeup of NZ rivers, altering the way they behave and migrate in flood events. Native vegetation is much less invasive, and generally establishes slowly by seed, and not by vegetative propagation.

At the same time that river channels were being modified in these ways, the clearing of forests, especially from the rolling to steep hill land that makes up a large proportion of the NZ landmass, has markedly affected catchment conditions and the supply of sediment and debris to and down waterways. Large flood events in early European times were very heavily laden with debris, and in the denuded catchments soil debris flows could form during intense rainfalls on saturated soils. A sequence of blockages from debris and sediment flows and then bursting flows down waterways gave rise to much more severe flood flows than runoff alone.

Initial flood management was mostly by earth stopbanks along river channels. Machinery was used to remove vegetation from channels, and reshape the channels of shallow gravel-bed river. Extensive use was made of gravel extraction from river beds for commercial uses in construction and road making. In many instances this resulted in entrenched waterways and distorted channels that have given rise to ongoing management difficulties.

Severe storms caused widespread catchment erosion and very extensive sediment deposition as well as flooding around NZ in the 1930s. In response, the NZ Parliament passed the "Soil Conservation and Rivers Control Act" in 1941, during World War II. After the war, major flood mitigation schemes were constructed along the lowland reaches of rivers, along with soil conservation measures in the pastoral hill country. The increasing availability of machines, and of increasing power and sophistication, gave rise to two major trends in river management.

Firstly, there was much more intervention in rivers, with the straightening of channels and the reshaping of the active gravel-bed areas of rivers, using draglines and bulldozers. This did result in the clearing from river beds of the invasive introduced vegetation, although the disturbed river beds facilitated a rapid re-colonisation, giving rise to repeated channel clearing. This activity also induced very significant alterations to the channel form and the pattern of low flow channels, braiding and flood overflow channels. At the same time, more substantial and higher stopbanks were constructed alongside river channels. Generally, these flood defences were close to the edge of main channels or the gravel bed area as present at the time of construction.[1]

Later, quarried rock was used to construct rock protection works along river banks, generally as a solid lining of the bank, using hydraulic excavators. This resulted in fixed river banks that prevented any further channel migration. However, a rock lining on one side of a river could aggravate erosion on the other side, as the river channel moved and flood flows were more sharply deflected across to the other side. The increasing use of rock works gave rise to more constrained channels, which increased bed scour and bank erosion pressures, hence generating the need for further rock works.

Vegetated margins were still widely used, and some intermediate strengthening measures were developed. This included fences of driven piles joined by two or three cables to form a flow retarding measure, without blocking off the flood flows within the vegetated berm land. The river edge of the vegetation was also strengthened by sets of permeable groynes spaced along the river bank. These permeable groynes could be made of different materials, but involved tied-together pile structures spaced at regular intervals along the river edge and oriented in a downstream direction. They deflected the main body of floodwaters away from the river bank, as small deflections, while still allowing a flow of floodwaters through the groynes and vegetation along the river margin.

The combination of highly mobile and powerful rivers with a low habitation density, but economic reliance on agricultural produce, has given rise to a particular approach to the management of rivers in New Zealand. Although it has involved hard edge protection works, in general rivers have not been tightly constrained, with relatively frequent interventions of channel clearing and reshaping, and the reinstatement or strengthening of margin vegetation.

Each river system has, though, its own history of modifications, and there are on-going and cumulative effects from past alterations of channel form, flow patterns and sediment delivery. These past changes affect the present river conditions, and hence potential future modifications and adjustments to river management practices. The river channel and margin vegetation has a particularly significant impact on channel form and roughness, and changes in vegetation extent and density can alter the type and planform of river reaches. The vegetative status of a river reach is, thus, critical to river management, and management options.

2.3 RESPONSE TO HISTORICAL MANAGEMENT PRACTICES

The starting point of the reassessment of past and present practices of river management was a better understanding of geomorphological processes, and how rivers are formed and

altered over space and time. In simple terms, rivers expend the energy they have from water flowing downhill on moving material, given form and friction energy losses from changing channel shape and vegetative interference. The movement of sediments, from catchment inputs and channel re-working, is thus an inherent associate of hydraulic (flood) flows, and hence also of the alteration and migration of channels.

River management to contain flood flows or to reduce erosion losses (of land or assets) directly affects channel width and form, and hence impacts on sediment transport, as well as flood levels and velocities. The relationship between flow containment, altered channel form and the scouring and deposition processes that move channel bed materials, was a fundamental principle of the review of management practices.

The aim was to work with the processes of nature, and not against them, and thereby achieve a more effective and cost efficient management of rivers over the longer term. The aim of engineering design is to select options that have the least overall cost in the long term (of many decades), where costs may be evaluated over a range of management objectives, and not just financial or budgetary costs.

The repeat aerial photography provided a means for assessing channel form and rates of change, and these changes could be related to the magnitude and frequency of floods and historical variations in the intensity of flood flows. Comparisons of multi-decadal records of aerial photographs showed similarities of channel form over time, with characteristic forms along given river reaches. Particular channel forms displayed a self-similar pattern, with the width and radius of curvature of channel meanders remaining the same as channels moved and were reformed by flood events. What was also notable was the repetition of these patterns of change over time in concert with the intensity of flood events. The nature of the channel would change as the hydrologic regime shifted from a quiescent period to one of more frequent and larger floods and then back again, but the shape and width of channels and their general meander form would remain the same, for a given regime, although differently located.

These patterns of channel form and behaviour indicated that a river reach had a characteristic way of behaving and range of variation. Determining the characteristic form of a river reach and its variability over time then provided the basis for an assessment of the space required for the river to maintain its natural processes associated with flood flows and sediment transport. From this a clear channel area could be determined along with zones of riparian vegetation on each side. This provided a defined area for the re-working processes of bed material transport, while allowing for channel migration and expansion, but with some containment of flood flows and erosion pressures.

The 'intermediate' approach that was developed in this way was a compromise, given the altered river conditions from past interventions, the confinement of the natural spread of flood waters and the vigorous growth of river channel vegetation. The 'heavy control' approach was expensive, and required continual repairs and maintenance because of the extent and rate of river adjustments to the works, while a 'retreat' option required the retirement of productive land and the management of large areas of vegetation.

The objective was to obtain better environmental and economic outcomes, by maintaining a more natural waterway that is managed in a way that recognises and works with river processes. This objective was, however, constrained in its implementation by many factors, including: the availability of river-side land, costs and economic impacts, funding arrangements, the presence of introduced invasive plants, the use of willows for river edge management, natural bed and bank controls that deflected and distorted channel features and meander patterns, artificial controls at important assets, and changes in upstream or catchment conditions.

3 NATURAL CHARACTER

3.1 River Diversity in New Zealand

There is a wide spectrum in river character and behaviour, depending on the catchment context of river reaches and the landscape conditions along reaches. Reaches may be tightly constrained by bedrock and have a limited capacity to adjust, or be within their own alluvial material and be fully self-adjusting, while maintaining a characteristic form. Along alluvial reaches, where there is continual interaction between the actively moving channels and a wider floodplain, a river can have different forms, from a single channel meandering within the floodplain, to a wide multi-channel braided river. These different types of alluvial rivers have varying levels of activity and rates of adjustment.

Defining the natural character of rivers is, thus, not straightforward, given the dynamic and changeable nature of river systems, responsive to the many influences of climate and landscape, as well as to human modifications of these influences. Alluvial river reaches can be particularly dynamic, and respond markedly to relatively small variations in climatic and landscape conditions, or human activities.

A river reach does, though, have specific characteristics, which depend on both its overall setting, of climatic regime (especially flood patterns) and catchment conditions (including geology and erodibility), and the local physical and ecological conditions along the reach. The natural character of any river reach depends on the interplay of physical forces of flow, sediment transport and channel resistance, and the ecology of the reach. This character is not fixed, but varies over time and along a river course. It is a dynamic expression of the processes at work and the variations over time and space of the influencing forces. It is more a matter of the processes at work than a specific state or channel condition. Thus, river reaches that have been modified by catchment and riparian changes can still have a natural character, through the expression of the processes at work. The channel dynamic and form will be different because of the different formative influences or changes in their strength and intensity, but it will still have the characteristics of a particular type of river reach, which occurs along rivers because of the natural processes at work in river systems.

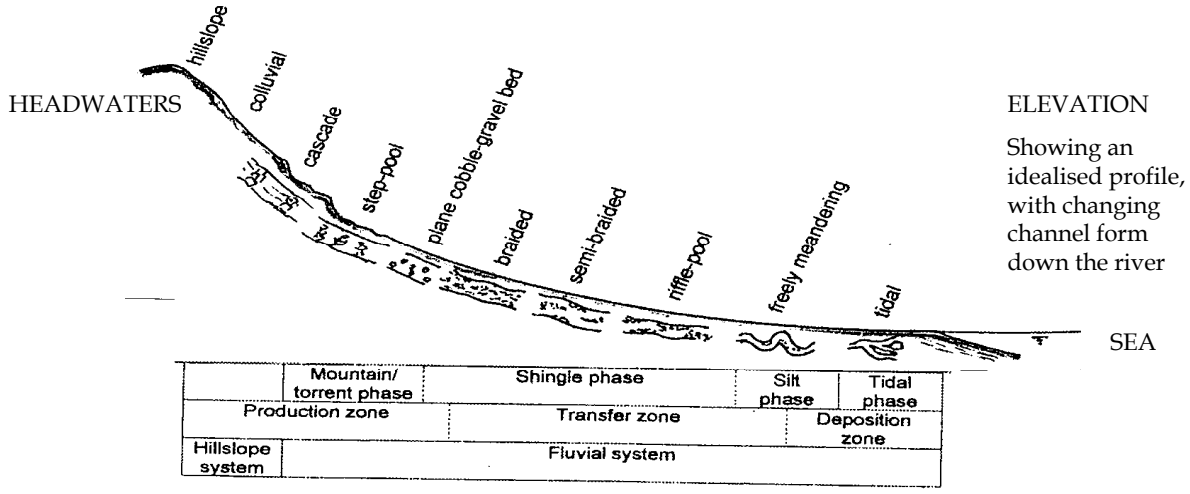
The natural character of a river changes along the river, from the headwaters to the sea. Hence a river is made up of a series of inter-connected reaches of differing character. Characterisation of the form (and formative influences) of a river is, therefore, most appropriately undertaken at a reach scale. It is a given reach that can be characterised, not a river. The nature, character and responses of a river change from reach to reach, as the forces and processes at work change, and a given character can only be defined for a reach where there is a similarity of river processes along it. A reach for river management purposes is then a length of river that has a relative uniformity of form and behavioural responses.

The reaches are connected within the whole river system, and there are patterns of reaches along a river with changes in channel character and river type. These changes can be gradual transitions or sharp transformations, as at the entry or exit from gorges. The patterns of sediment delivery and storage will also vary from catchment to catchment, with varying degrees of connectedness, or efficiency of sediment supply. Any factor that changes the flow or sediment regime in a given reach may alter the process relationships along other reaches, and hence the river form of the reaches.

The diagram below (Figure 2) is an example of the characterisation of changes in channel form down a river.

Figure 2

RIVER TYPES — Down a River



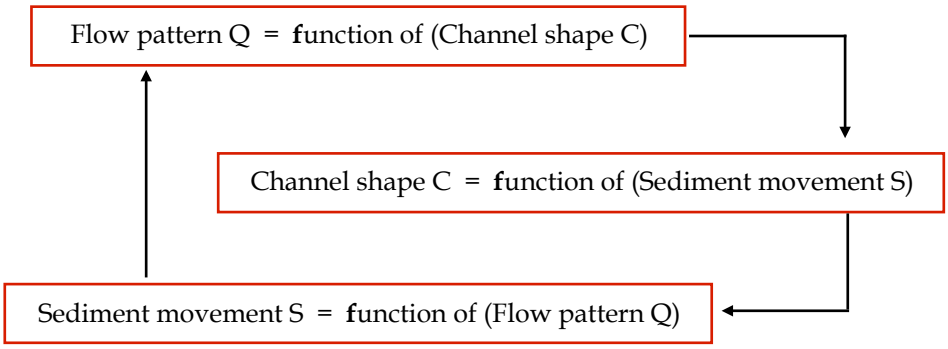
CREDITS: "Gravel Bed Rivers", by Paul Mosley & Stanley Schumm

These changes in channel form, with their different characteristic behaviours, occur in both space and time. From steep forested headwaters to wide flat marshy alluvial plains, rivers change their form. Over time rivers evolve, changing in response to climatic variations or alterations in the pattern or intensity of floods, and to tectonic events and changes in the landscape and sediment supply factors. These changes alter the ecology of the river, which in turn feeds back and alters the physical processes and form of the river. Human activities can modify many of these relationships and evolving trends, accelerating or suppressing natural tendencies in differing circumstances. Thus the type of river found at a given location may change, or evolve, over time. Climatic or land use changes, construction of dams or constraining flood defences, alterations to riparian or floodplain vegetation and aquatic habitats can all impact on the flow and sediment regime along a reach, potentially changing its river type and characteristic behaviour.

The natural character of an alluvial river reach, in its physical expression, arises from a complex interplay of the flow forces, the rate of supply and nature of the river sediments, and the channel form and resistance to erosion of the river bed and banks. The self-similarity of river channels, that form and re-form to a characteristic pattern from flood to flood, arises from an interconnection or feedback loop between flow pattern, sediment transport and channel shape. Flow pattern is a function of channel shape. Channel shape is a function of the erosion and deposition processes of sediment transport. Sediment movement is a function of the flow pattern. Thus, while the river channel moves, its form stays the same, maintaining a characteristic form at a reach scale, for a given regime of influencing factors. The diagram below (Figure 3) expresses these relationships as a feedback loop connecting these aspects of the physical behaviour of rivers.

Figure 3

INTER-DEPENDENT PROCESSES — Flow/Channel/Sediment



This interplay of form and function, as water and sediments pass down the river system, can be constrained or modified by the interactions of the river with its landscape. Sediments are stored on the floodplain and older deposits removed by the interactions between the active channels and the adjacent floodplain. Base rock in the channel bed will restrict bed scouring and direct the sediment transport processes to the banks. Conversely, rocky or cohesive banks will restrict bank erosion, and deflect channel migration.

The river ecology, especially its riparian tree vegetation, interacts with this physical process regime, and can substantial affect these physical processes and their interconnected expression.

Rivers and their margins have an especially diverse ecology, given the availability of water, edge effects, and the dynamic interactions between surface and ground water, and channels and floodplains. The ecological systems are highly linked and inter-dependent, with many complex interactions between the biology of flora and fauna along waterways and the physical nature of the waterways. The physical processes and ecological relationships of aquatic and terrestrial habitats form an inter-dependent and inter-connected system. Most noticeable are the interactive effects of vegetation in rivers, with river margins providing diverse vegetative habitats, and vegetation affecting the channel form through island colonisation and channel splitting. The deposition of logs and snagging of vegetative matter can affect the formation of bars and pools, while also encouraging the growth and spread of vegetation within the channel.

The interactive processes of the physical dynamics are, thus, modified by the river ecology, and especially by the in-channel woody debris and riparian vegetation along the river course.

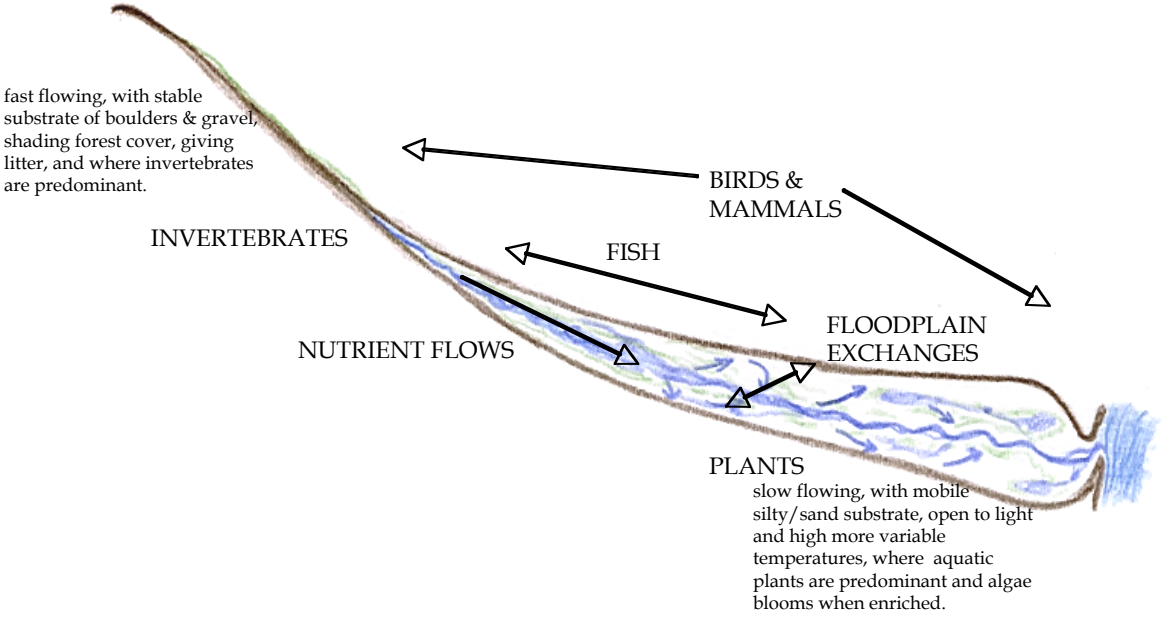
There are different drivers of these waterway ecosystems. The primary biological energy input to a forest stream is the leaf litter, while the primary energy input to an open river channel is from in-stream algae and macrophytes. This gives rise to very different aquatic eco-systems, which in turn impact on the channel form. In many instances, floodplains have a wide range of habitat types with complex interdependencies, and they have an essential role in maintaining the ecological functionality and health of a river reach. A fundamental connectivity arises from the exchange of nutrients between river channels and floodplain land through groundwater flows. These groundwater flows and nutrient exchanges vary along river courses and in different types of rivers.

A very simple diagram, which shows some of the main ecological interactions along a river and its primary ecological base, is given in Figure 4.

Figure 4

ECOLOGICAL PROFILE — Along a River

Biological activity adds layer on layer of interconnected processes, which give rise to very complex and dynamic river systems of inter-dependent ecosystems and physical exchange systems.



A characterisation of waterways would then extend beyond a determination in terms of the physical features of river reaches. Along with physical form, it would include the hydrological regime (flow variations over time), the riparian (and floodplain) vegetation or habitats, and the aquatic life (invertebrates and fish). An assessment of the natural character of a river reach can then be undertaken in terms of a number of broad categories, with each aspect or influence determined or characterised in a manner that is appropriate to its form, pattern, speciation or behavioural type.[45]

In the approach to river management outlined in this paper, the physical template (and associated process interactions) provides the platform for assessing appropriate river corridors and active channel areas. Hence the focus is on the physical processes of rivers and their interactions with riverside vegetation.

3.1 River Responses in New Zealand

Rives evolve over time and space. They change in response to altered boundary conditions and influencing factors, such as geological upheavals and climatic shifts (for instance, of glacial and interglacial cycles).

New Zealand lies on a tectonic plate margin, which is characterised by active mountain building and block faulting. Frequent earthquakes, with fault movements and associated landslides, as well as volcanic activity, affect river systems. This geological activity determines and continually alters catchment form, of valleys and hill slopes, and river profiles. It also influences the supply of gravel bed material to river systems. Over geomorphic time frames, river systems trend towards a dynamic equilibrium that balances

these various formative forces and influences. However, many New Zealand rivers are unable to establish such an equilibrium because of the geologically active and high-energy environment of New Zealand. The uplift and incision rates vary across the landscape and over time. Hence, the past and more recent geological and landscape history is an important part of the catchment setting of a river system.

Over the last 2 million years, of the Pleistocene period, there have been marked swings in climate, from cold glacial periods, with large ice caps at the poles, to relatively warm interglacial periods, as at present. Sea levels have gone up and down, with ice accumulations at the poles lowering sea levels by over 100 m compared to interglacial periods.

These climatic changes have impacted on the character and sediment transport processes of rivers, resulting in alternating long-term trends of aggradation and degradation. In glacial periods high sediment supply from the steep catchment land results in valley infilling and low land aggradation. On present-day coastal and inland floodplains there was sediment deposition and re-working, with river courses extending beyond the present coastline, down to the lower sea level. In the shorter interglacial times the forest cover reduces catchment erosion, but more intense rainstorms degrade the rivers, which incise into the deposits laid down in the glacial period. Remnant surfaces and terrace formations reflect recurrent phases of activity. At the same time, the higher sea level gives rise to aggradation and plains building at the coast, with coastline accretion or wave attack retreat, as a new coastline forms.

Similar aggradation and degradation trends occur under present (interglacial) conditions. Variations in catchment erosion and sediment movement between common and more extreme flood events give rise to down-river pulses of sediment, which can move as a sediment wave down river systems. Large storm events create high sediment input from the steeper upper catchment, and a flushing out of the lower reaches by the large flood flows. In more common flood events the upper catchment input is re-worked down the system and the lower reaches re-built.[7, 9]

Particularly severe storms can destabilise catchments, giving rise to large erosion scars and greatly increased sediment input from the event itself and for many years afterwards.

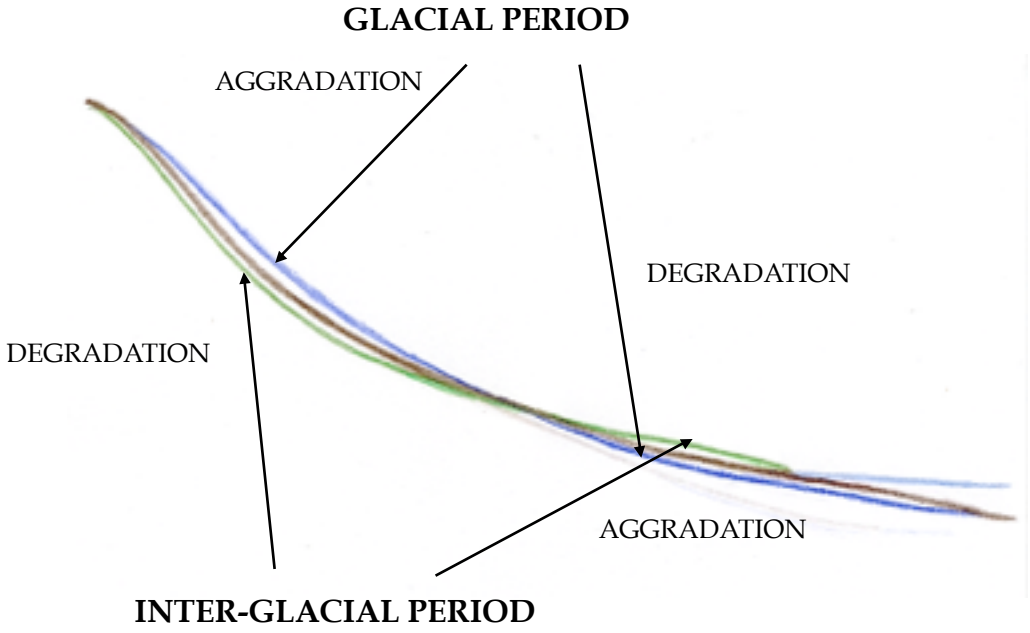
These oscillating trends in river dynamics and transport of sediments are indicated in a very general way in Figure 5, for the conditions during glacial and interglacial periods, and for extreme and more common events under present climatic conditions. These climatic variations and geological activity give rise to complex landscapes, with diverse and system-specific interactions of rivers with their watersheds and floodplains. River dynamics is affected by paleo-deposits and other legacy features, with these features arising from past activities over a long period of time.

Thus, any given catchment has its own legacy of geological and historical features and effects. Variations in these catchment conditions have differing impacts on the contemporary dynamics of river processes. For example, the amount of sediment that is available for transport by a river system can be significantly affected by legacy effects, such as the stores of moveable sediments along river courses and their adjacent terraces.

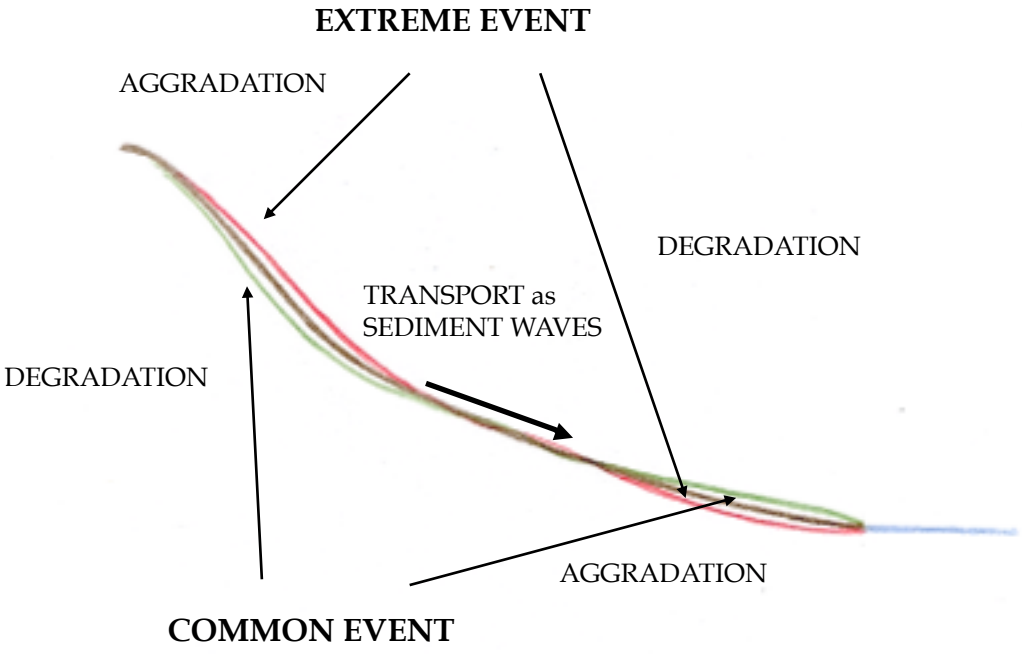
Figure 5

RIVER PROFILES — Flood Intensity & Climate Change

Sediment transport and channel trends in Glacial and Interglacial periods



Sediment transport and channel effects between Common and Extreme floods



In general terms, finer-grained materials from former glacial periods underlie the contemporary river bed materials laid down by the current flow regime, along many New Zealand rivers. This layering of different materials can affect river processes, especially

during large flood events. When uncovered, exceptionally large and deep scouring of the underlying finer-grained sediments may occur, inducing geomorphic instability.

The pulse input of materials from the longer term periodicity of storms and the severe catchment erosion and sediment input of large events, gives rise to a wave-like movement of the bed material gravels down river systems, as the storm deposits are re-worked and transported downstream. Bed levels at any given point will, then, vary due to channel migration and the throughput of these gravel waves. This variation in sediment movement also impacts on the channel form, which varies as the sediment waves pass through.

The particular expression of these processes and trends varies markedly within the New Zealand landscape. The evolution of a river system and the trajectory of change at a reach scale is greatly influenced by the pattern of sediment transfer and distribution of storages throughout the system. It is the connectivity of the system and the ability of a river to adjust its form within its containing landscape that determines its channel patterns and the characteristics of its reaches.

Understanding the various timescales of river adjustment and their catchment to catchment variability is crucial to an appreciation of sediment transfer processes and rates, and hence channel patterns and their variability, in any given river system. The particular nature and history of a river is fundamental to a determination of the appropriate space to allow for the natural processes of a river along a given reach.

Thus, the character of a reach varies over time, at different time scales, and this can give rise to changes in the type of reach, active channel widths and the patterns of channel adjustments. This reach character can be affected by recent human modifications of the landscape, as well as recent significant natural events.

Any channel design and overall river corridor has to take into consideration this variability and longer term trends in river behaviour.

4 METHODOLOGY

4.1 GENERAL

The assessment of the natural character of a river reach and the determination of appropriate design channels and management corridors is based on investigations of the geomorphologic context of a reach, its channel patterns and how they change over time, and analyses based on the main factors that influence channel formation and variation.

Studies of river characteristics and the processes of sediment transport and channel formation are undertaken within a catchment context, to provide the climatic and catchment setting of the reaches under consideration. The natural channel form and its variability over time, in relation to climatic cycles and other influences on catchment processes, is assessed for any given river reach, from aerial photography and early survey plans of the reach. Surveyed channel cross sections provide information on channel trends and sediment transport processes, directly and through hydraulic modelling and transport calculations.

Empirical formulae of channel widths, which have been derived from theory and field studies of natural meander forms, are used to determine design channel widths (see Attachment 2). These formulae are based on the main river forming influences of flood flows, channel slope and bed material size. The layout of design channels or multi-channel fairways, where active bed load movement takes place, is then guided by these design channel widths, and wave form relationships between width, radius of curvature and wavelength. The design channels or fairways are adjusted to follow the existing river

course, with account being taken of the existing channel area and alignment, given natural and artificial constraints or control features.[5, 6, 8, 10, 14]

From this, appropriate active channel areas and margin vegetation buffers are determined, to give a defined river management area. This management is directed at the maintenance of generally clear channels or fairways for the active working of the river bed material, and of dense vegetation margins that buffer and absorb the channel migration associated with the channel re-working processes. The development of this management area takes time, as vegetation has to be established, cleared and re-used, depending on where it is within the design area. The aim is to have a clear gravel area, with minimal roughness/resistance elements other than what arises from channel form and boundary conditions, within restraining but flexible boundaries of riparian vegetation.

The natural form of the active channels along the reach can also guide in-channel works and alterations to the active channel, and the curvature or layout alignment of edge strengthening measures. The more detailed layout of works and shaping of channels then follows the natural channel forms and movement, with the aim of being both more effective and less disruptive of the river environment and its natural conditions.

Beyond the active channel and margin buffer zones, a wider river corridor is drawn up that includes reserve areas and allows a more diverse riparian environment. This wider river corridor defines the overall space sufficient for the river to adjust according to its natural dynamic, over periods of differing flood patterns and intensity, and potential catchment changes. The active channel area and management buffers are, thus, set within a wider corridor, and they can move within this corridor over time.

The channel form, along with the extent and width of margin buffer vegetation, depends on the type of river reach. Four types of alluvial river reaches, where channel beds and banks can be moved and altered, have been differentiated for this design process. These reach types cover most of the managed reaches of gravel-bed rivers in NZ, which are generally along lower reaches on plains or within relatively wide valleys with a valley floor of alluvial materials. The river types used can be briefly described as follows:

Single Channel:

- **Meandering** — well defined single sinuous channel, with inner point bar and oscillating sectional asymmetry around bends, with a slow migration of the channel as a whole in a downstream direction.
- **Alternating Bar** — well defined low flow channel, meandering around alternating bars, and migrating within an overall (active) channel that has some meander curvature and definition within the floodplain.

Multi-Channel:

- **Semi-braided** — semi-defined main channel with mobile channels that migrate within an area of gravel bars and islands, and with back channels and flood overflow paths across a wider partly vegetated area.
- **Braided** —wide gravel bed area of multiple channels that continually shift and re-form in flood events, with shallow flood flows of concentrated flows that move across the bed and give rise to rapidly moving channels and highly pulsating bed material movement.

Aerial photographs of river reaches in New Zealand that show different channel forms are given in Attachment 1.

The first step in the drawing up of a design channel (for single channel reaches) or fairway (for multi-channel reaches) is to select the appropriate reach type. This effects which

empirical formula is more applicable or what combination/arrangement of channels will most suit the reach. Selecting the reach type is, though, normally straightforward, as they look different and the rate and manner in which channel migration takes place is different.

Particular meander forms are observable at different scales in the different types of reaches, with individual meandering bends being part of a larger scale meandering pattern, while a meandering curvature of braid belts is commonly observed in wide fully braided river reaches. There is a scale repetition of meandering within meandering features from single channels to wide multi-braided reaches. The theoretical meander forms that the formulae relate to and are associated with the threshold of motion of the bed material or with live-bed conditions of flow dominant meandering, can then be related to these reach types and hence guide the determination of design channels or fairways. Although the formulae were not necessarily derived for this purpose, they can be used to represent the different channel forms and patterns in the alluvial river beds of these different river types.

Example diagrams of these meander forms within design channels or fairways are given in Attachment 2. They show diagrammatically how different meander forms can fit within each other. One is taken from the report on the original investigations of the "Upper Tukituki" scheme, and the other from the river characteristics and sedimentation report on the Hutt River, which was part of the floodplain management plan investigations for the floodplain of the Hutt River valley.[18, 24]

An understanding of the geomorphological processes at work along different types of rivers is useful in determining river types and for the design process as a whole. However, a detailed understanding of the different processes and ways of behaving of alluvial rivers is not essential for the practical application of the design method to determine appropriate active channel areas and vegetation buffers for river management purposes under the prevailing conditions. It has been applied as an engineering practice to assist in a form of river management that provides more space for river activity and more effective management because it is based on the natural processes and character of alluvial rivers.

Some pointers on the characteristic behaviour of different types of rivers can, of course, be useful, but the differences between the river types of the design methodology of the practice being outlined, makes the type selection reasonably obvious. Single channel meandering rivers migrate across the available valley floor, and have distinctly asymmetrical sections at bends, with an inner side point bar and relatively deep pools alongside steep outer side banks. Alternating bar channels have longer lateral bars along alternating banks, which tend to translate downstream within some relative confinement. When there is lesser edge confinement and more activity or mobility along a reach, the channel becomes partly braided, with side channel and islands, and in floods back channels that have become quite vegetated then become active. Braided rivers have multiple channels that freely migrate and shift positions during flood events. The channels or braids continually change, with a complex arrangement of runs, riffles and pools as the channels bend, converge and diverge.

These river types have different capacities to adjust, and differing sensitivities to changing inputs and riverside conditions. Studying catchment conditions to assess sediment and debris supplies, the system storage and translation capacities, and how this may vary over time is, thus, an essential part of the design of the wider river corridor. The likely range of reach-scale channel adjustments over the longer term is important for the determination of the river corridor, within which river processes of sediment transport and channel adjustments, and the management of these processes, takes place. These adjustments will be of a different nature and scale for different river types, and are catchment and reach specific.

The most difficult part of the design process is the determination of longer term trends and the magnitude of channel variations with changing conditions, and hence the defining of the outer limits of the river corridor. This is where an understanding of the geomorphic processes at work within the catchment and along the management reaches is most helpful. Any assessment of longer term trends does, though, depend on the information available about the specific catchment and reaches, and there is generally a paucity of relevant geomorphic data for most river systems in NZ. The assessment of likely changes in river behaviour and the magnitude of channel variations over time for a given reach within a particular catchment context is generally qualitative and experience-based. Because of this, a methodology for this part of the design process cannot be spelt out. It is something that has to be learnt and applied site by site. A precautionary approach is, therefore, recommended when setting wider corridor boundaries, using whatever relevant information is available on the varying width of the active areas of river processes over the longer term along a given reach.

Given a defined active channel area and margin vegetation buffers, the aim of the management approach is to allow the margin buffer zones to absorb the erosion and deposition processes of the river, without an encroachment beyond the river corridor into productive land or to threaten valuable assets. The buffer vegetation is lost and re-established over time as the river channels move and migrate, with sufficient width to allow a slow re-establishment of lost vegetation over time, as the river naturally moves on and erodes other areas of the buffer. Remedial action can, therefore, be less intensive, with greater reliance on the re-establishment of vegetation over time.

The buffer zone can also have sufficient width to provide a reserve for channel widening during high flood intensity periods, and to absorb the impacts of severe events. This may, though, have to accommodate changes in reach type that substantially increases the active channel width during periods of high flood intensity, as compared to more quiescent periods, or for predictable changes in river conditions because of changes taking place in the upstream river and catchment. The overall river corridor should, therefore, define a suitable area for the river over the longer term (of decades). The outer boundary of the river corridor then provides a line beyond which productive uses can be made of the land alongside the river reach.

4.2 DESIGN PROCESS

The design process can not be explicitly explained as a well-defined procedure, because of the variability of rivers and their complex dynamics. The same approach has, however, been applied to many river reaches in NZ, of different river types. The design methodology can then be described in terms of the information used and the general methods applied.

The reach type and its general character is first assessed from the catchment and climatic setting and reach conditions along the river. A given reach is determined by its geomorphic context and connections, with a defined reach having a relatively consistent form and similarity of behaviour over time, so that it can be considered as a unit in terms of river processes. Reaches may be further subdivided by management objectives and the presence of artificial constraints. This differentiation in terms of management requirements is, though, a secondary matter, that follows on from the geomorphic determination. At the same time, the identified reaches that have a similarity of form and functional character are connected to, and conditioned by, the larger river system. This connection to the river system as a whole has to be recognised and kept in mind when analysing specific reach conditions.

The investigations of river characteristics, to determine the wider context and reach type and variability, include an assessment of the geological and climatic history of the

catchment and salient present and past impacts on the current river conditions. The assessment of a reach then involves the study of repeat aerial photography and historical survey plans of the river reach, and the semi-theoretical analyses based on the empirical formulae for channel widths.

The historical record from aerial photography and plans show the channel patterns and temporal rates of migration, movement and alteration of these patterns. When aerial photography is available over a long enough time period (decades), the change in reach type with changes in the hydrological regime and/or sediment input can also be observed.

Based on this assessment of the reach character and its channel form, the appropriate regime formula and its associated channel width can be determined for a design channel or wider multi-channel fairway. The reach assessment should consider the wider context of: the flood history and how the present channel relates to cycles of quiescent and intense flood periods; the pattern and extent of vegetation, and vegetational trends; sediment input rates from the upstream catchment and riparian re-working, and whether the reach has a degradation or aggradation tendency; bed material stability and likely changes in substrate composition.

In addition, river channel surveys, which are mostly surveyed cross-sections at intervals along the river course, provide information on the magnitude of cross-sectional variations over time and along the river. They also provide information on channel slope, including the location of significant changes of slope. Channel resistance can be derived from hydraulic modelling, when this is available, using the channel cross-section data, and sediment transport rates assessed from the modelling output, using appropriate sediment transport formulae.[46]

Repeat channel surveys provide a record of cross-sectional changes over time, and appropriately spaced cross-sections allow hydraulic modelling of given flood flows. This aids the assessment of river conditions and allows a quantitative estimation of sediment transport rates.

Information on the bed material is required for all the meander theory formulae, and for estimation of bed load transport rates. The size of the bed material can be obtained from samples of bed material taken from the river channel, which are then weighed on site or sieved to give size grading curves. There will normally be considerable variability in the size gradings from sample to sample, and in gravel bed rivers a heavier armouring layer is generally present on the surface, where the bed material has been actively worked within a channel or braid. The median size of this armouring layer is used in the meander formulae, while the median size of the whole of the bed material is used in the transport formulae.

The method that has been used to determine bed material sizes involves selecting an area that is representative of the bed armouring, and then taking a surface layer sample in a consistent manner, to give a standardised sampling. When grading curves are determined from a number of samples that represent the range of bed material at the site, and a combined grading obtained, then a very approximate relationship has been found to hold between this grading curve for the whole of the bed and a grading curve of just the armour layer. The median (50%) size of the armour layer is then generally about the same as the 75% passing size of the whole of the bed.[46]

Photographs are taken of the samples, prior to removal and afterwards. A library of these sample photographs from river reaches around New Zealand, which have been graded, allows photographs of surface bed material to be compared with the photographs of the graded samples. This photographic library covers many different reaches and river types.

The 2 year return period flood flow is taken as a representative flow for the power of flood events, and this dominant flood flow is used in the meander formulae. It can be determined from flood frequency analyses of flood flows at recorder sites, or from flood estimation procedures using rainfall data and catchment area, or regional flood estimation methods. Reasonable estimates of the 2 year return period flood flow can be obtained from short periods of records, and transferred along a river using factored catchment areas.

The empirical formulae have been developed in different ways on different types of rivers, and the use of a dominant discharge is a very coarse proxy for the power of a spectrum of flood flows. It may not be representative of the channel forming power of flood flows. However, the application of the formulae and their use in defining channel widths has been found to apply consistently and fit the actual river channels of many river reaches and river types in New Zealand.

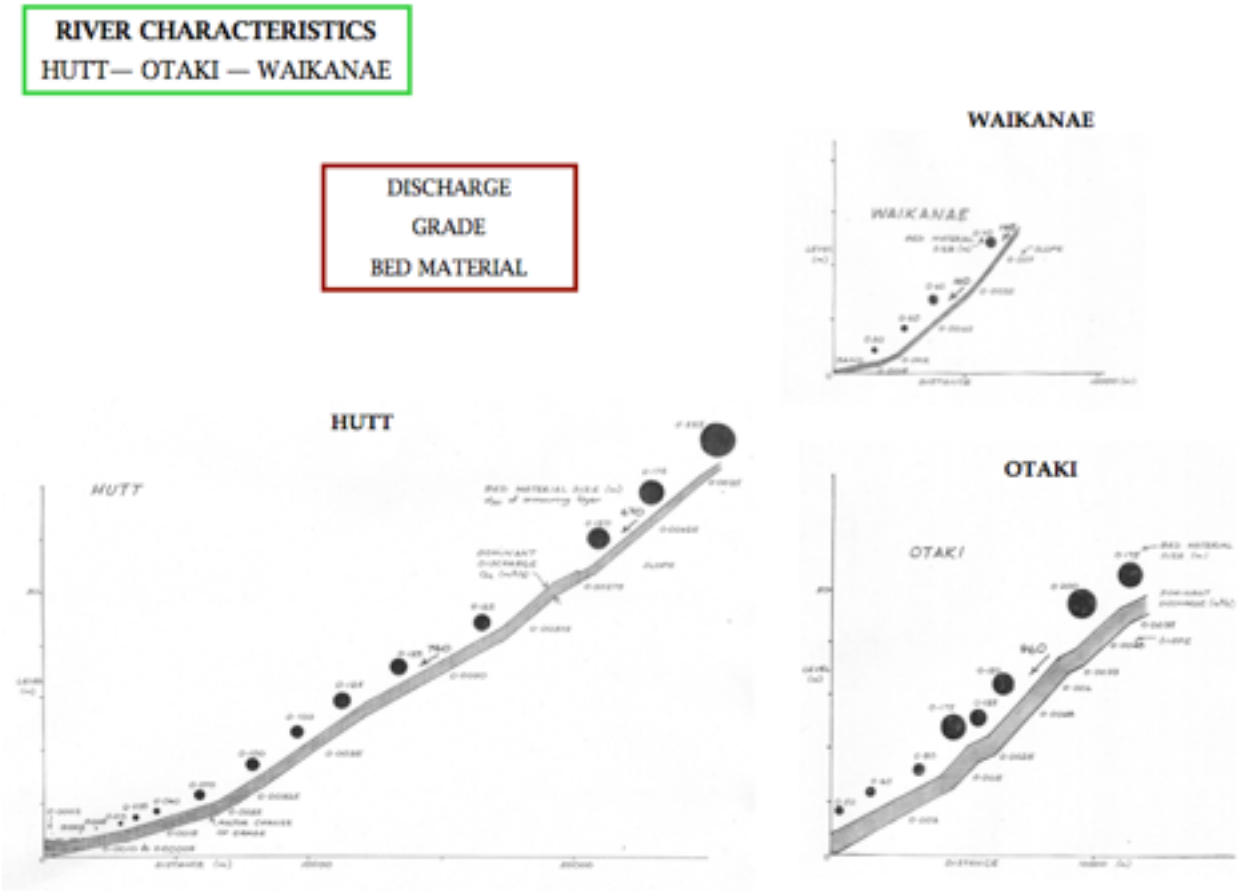
The meander formulae for channel widths use different combinations of the main channel forming characteristics of flood flow, channel slope and the size of the channel bed material. They have been found to relate well to different channel forms and meander patterns, and hence provide a design basis that can be consistently applied. Simple wave form relationships are then used to relate these widths to the radius of curvature and wavelength of channel meanders and design fairways.

The formulae used for the design channel or fairway determination are given in Attachment 2. This attachment includes a table of results for selected river reaches from regions throughout NZ. Examples are also given of tables that have been used to summarise the formulae and their design applications. These data show the variation in the influencing factors and in the resulting widths given by the formulae, for a wide range of river types and reach locations around NZ.

A diagrammatic representation of the three main channel forming influences is given for the Hutt, Waikanae and Otaki rivers of the Wellington region in Figure 6. The river slope or grade is given by the profile, the dominant discharge by the thickness of the profile line and the bed material size by the diameter of the circles. This example shows a typical variation in these river forming influences for rivers in the same region, which all flow from the Tararua Range. Bed material changes can be affected by human activities, such as gravel extraction from the bed, as well as natural variations in these influencing factors, and this is notable along the Otaki River.

Figure 6

CHANNEL FORM — Influencing Factors



The channel width formulae have been derived from measurements on different types of rivers, and relate to channel forms under different regime conditions. The formulae do not, though, define the plan configuration of the channel, and the type of channel has to be assumed from the general nature of the river when applying the results of the regime formulae, as outlined above.

The channel meandering and migration also takes place in different ways and at different scales in river reaches. As noted earlier, there is meandering within meanders, and meandering channels can be contained within a larger scale of meandering. In a wide braided river the movement and meandering of braids takes place within a meandering 'braid belt' that itself moves with a characteristic meander form. In small single channel reaches bed material movement can be constrained, and there is one meandering channel with alternating bars. Meanders related to the threshold of motion of the (alluvial) gravel bed material form within an active channel that is semi-braided and where this active channel form moves it does so to a meander form as well.

The determination of the channel pattern and its make-up in terms of meandering channels at different scales is critical to the selection of a design channel or fairway for a given river reach.

The diagrams of design fairways and channel meanders in Attachment 2 are schematic examples of how different channel meanders fit within different design fairways.

4.3 DESIGN CHANNELS

Once an appropriate channel type has been determined for a reach, a design channel or fairway can be drawn up that suits the river alignment and channel area, fitting in with the natural constraints or controls on the channel position, as well as artificially imposed constraints from human activities and assets. The design will generally be drawn up to fit the existing reach alignment and channel configuration. However, it should be understood as just one design possibility, and as reach conditions change over time, from normal channel movements, or due to changing influences external to the reach itself, the design may have to be altered to suit. While the pattern of the reach channel(s) and their overall number and extent can persist over time, for similar influencing conditions, the actual position of channels and their meandering within the active bed area will move as part of natural river processes. There is a pattern that stays the same while its expression constantly changes.

There is, therefore, always some flexibility in the drawing up of a design channel. Consideration should always be given to the likely trends and the time span of changes that would impact on the design, as a management guide. It should be consistent in width and with a well-formed alignment, which reflects the natural character and form of the reach, but it is not something to be rigidly followed. The design lines indicate an overall alignment and average width over time. They guide the extent and layout of river management measures within the active channel area and margin vegetation zones. The actual width of the active channel and vegetation buffers will vary over time, within the wider river corridor that allows for varying reach conditions.

Thus, any design relates to particular prevailing river conditions and the current alignment of the river reach. If these river conditions change significantly, then the design and the associated river management methods must be re-assessed, and revised as necessary to fit different conditions.

The design channel, or fairway of multiple channels, is based on relationships about river channel forms and widths. The design width provides an appropriate area for the channel adjustments that take place along a reach in a manner that relates to the channel movements of the reach. The design widths, therefore, depend on the reach type and character, with the reach type being determined first, and then a design drawn up for that type of reach. These design widths are for unconstrained rivers, and the design must be adjusted to take account of features that constrain its adjustment capacity, and hence impact on the river and its channel form or alignment.

The relationships between channel types and the empirical determinations of channel widths are used to select an appropriate width for a given reach type. The way in which different design channels or fairways are then determined for different types of rivers can be described as follows.

The smallest meandering channels of gravel-bed rivers are formed as 'threshold of motion meanders', which are determined by the ability of flood flows to move the bed material, and they become fixed on flood recessions, as sediment transport stops. They are seen as low flow channels in gravel-bed rivers. There are two forms: a narrower meander based on the regime slope for the reach; and a wider meander based on the actual slope of the reach. The narrower meanders tend to be well formed, with a radius of curvature of around 4 times the width. The wider meanders tend to be somewhat distorted, because of the slope adjustment they accommodate, and have a radius of curvature of around 6 times the width. There also tends to be an oscillation between these meanders, to achieve the slope adjustment, with a corresponding change in the radius of curvature.

Where a river reach has a meandering single channel form (Meandering type), or has a relatively tightly constrained single channel within its floodplain materials (Alternating Bar type), then a narrow design channel, based on the threshold of motion meanders, can be applied. This gives a well defined channel which can have a consistent meander amplitude and wavelength, generally using a radius of curvature of 4 to 6 times the width.

For meandering single channel reaches, with well-defined bends, this design channel is lined by a buffer zone around the outer bank (erosion) side, with the buffer width taken as that of the smaller meander width. This well defined channel has a natural tendency to migrate in a downstream direction. Some allowance has to be made for this channel movement when defining the channel and buffer zone areas for management purposes.

For constrained single channels that are relatively straight, the design channel is lined by buffer zones continuously along both banks. For this type, wider buffer zones can be used, depending on the erodibility of the banks and floodplain materials.

These reaches are generally along floodplains where the alluvial deposits are relatively coarse and more resistant to flood flows, or where flood flows spread out over the floodplain and in-channel flows are relatively weak. They can also occur where the river has an under-sized channel within a landscape formed under a different climatic regime, generally that of the preceding glacial period.

This design channel can also be applied where the river is already constrained by past river management, and it requires the highest level of on-going management. In these circumstances, a particular channel alignment and meander pattern, of many possible channel positions, is defined and has to be maintained. Downstream translation of lateral bars will continue to occur. Consistency from bend to bend is important in order to minimise long term river management efforts under this regime, without any one bend becoming especially enlarged or over-sharp. Thus, consideration must be given to what is happening along a series of bends, assessing the downstream responses from management interventions at any given bend.

This **threshold of motion** meander form is, thus, applicable as a design channel for management purposes, to narrow and well-defined single channels of either the Meandering or Alternating Bar type. This single channel form may exist naturally within the river floodplain, or arise from past management as a response to channel confinement.

Where there is a less defined and more mobile main channel within a wider channel area, then a wider design channel can be applied, based on the 'dominant flow meander' width that arises when flood flows of a dominant flow or greater can fully mobilise the river bed material. This channel width provides sufficient space for the active main flow channels to migrate, within a channel area edged with buffer zones of tree vegetation. The threshold of motion meanders associated with bed material movement can then migrate within this channel, with adequate curvature, but with not so much curvature that they tend to split up or form sharp cross-overs that directly attack the bank and buffer vegetation. In this case the radius of curvature of the meanders is taken as 4 times the width. The buffer zones on each side restrain and absorb the meandering flow channels, and the buffer width can be based on a full width incursion of the wider threshold of motion channel. This provides sufficient width to accommodate some channel migration and its associated erosion, with the buffer vegetation being re-established as deposition occurs with further channel migration.

Under this management regime the buffer zones do not have to be repaired so promptly following erosion damage, and reinstatement can take place over a period of time, as river conditions change and main flow channels move. Thus wider buffer zones are used, but repairs are less expensive as more gradual reclamation of eroded areas can be achieved

using mainly vegetative means. The wider channel is, though, more prone to re-vegetation, especially by vigorous introduced species, and some regular channel clearing, especially of higher bar areas, may be necessary if this design width is used.

This **dominant flow** meander form is applicable, as a design channel, to river reaches that are relatively mobile, with a main low flow channel and gravel beaches (bars), and may have secondary channels and flood overflow paths. It provides more space for channel movement in Alternating Bar reaches, and can be applied as a relatively contained channel for Semi-Braided reaches. It allows the channel movement associated with the transport of the river bed material, with sufficient space for the processes of bed scour/deposition and bank erosion/accretion of this movement, but does constrain the overall width and alignment of the river, reducing its natural variations and wandering within its floodplain.

Where there is sufficient space available, and the river tends towards a wider semi-braided to braided form, then an even wider design channel, or fairway, can be applied. In this case the fairway is taken as 1.7 times the dominant flow meander width, as this provides sufficient space for this dominant flow meander form to migrate along the channel with a minimum of restraint (at a meander sinuosity of 1.1 to 1.2), but is sufficiently narrow to inhibit channel splitting. For relatively wide gravel-bed rivers this width is a good compromise between the conflicting requirements of minimised bank attack, low flood rise, efficient sediment transport and reduced channel area.

The management approach is, then, one of quite frequent but low level interventions, mainly of channel clearing and re-vegetation of eroded areas within the buffer zones. For a mainly vegetation, soft edge, approach to river management, the buffer zones have to be correspondingly wider, and are normally the width of the dominant flow meander. Localised strengthening of the channel edge may still be necessary, to reduce buffer zone losses and assist in re-establishment after loss.

This **fairway** design is applicable to wider channels of a Semi-Braided or Braided type, where sufficient area of floodplain land is, or can be made available, to provide the space for the channel changes that naturally occur in these reaches of rivers.

The wider the design channel (or fairway) the wider the buffer zones on each side, and the width of a meander form smaller than that used for the design channel can be used to determine the buffer zone width. The buffer zones can then be determined in accordance with natural channel forms, and thereby be consistent from river to river and for different types of reaches. In general, the buffer zone width, using this approach, is about a half the design channel width.

Different buffer widths could be used, giving different overall channel widths, of active channel areas and vegetated margins. Narrower buffer zones have been used, especially in the earlier applications of this approach to river management. However, the wider buffers provide more space for channel widening and changes in channel form during periods of high flood intensity. The adequacy of the buffers is really a matter of experience over time and on a range of river types. However, a general rule based on meander widths, as determined from theory and practice, has been used for the intermediate management approach outlined in this paper.

For wide fully braided rivers, where braid belts form and move as a whole, and large islands can form within the active riverbed area, an even wider fairway is necessary to suit the larger scale braiding pattern. In this case, fully developed braid belts meander as a whole, and they have a similar form relationship to the meanders of semi-braided or single channel reaches. However, the design fairway width has to be determined empirically using a series of repeat aerial photographs of the river reach, and any other photography or plans of braid movement. The meander belt widths and their overall meandering trends

are determined from a comparison of braid patterns within a reach and their movement over time.

Experience with fully braided rivers in New Zealand has shown consistent widths to meander belts of well-formed multiple braids. A repeating pattern in the changes in channel braiding has been observed, with a split form developing at a relatively well defined channel width. The channel widening response (and vegetation clearance) with large floods or periods of high flood intensity, which occurs in single channel and semi-braided rivers, is also seen at a larger scale in fully braided reaches. This wider fairway design, based on widths that do not have a split form around large islands has, for instance, been applied to large Canterbury rivers, such as the Waimakariri and Waitaki rivers.

4.4 RIVER CORRIDOR

Once the appropriate design channel or fairway has been selected for a given reach, an overall river corridor area can be defined. This corridor should be sufficient to provide enough space for the river channel and the vegetation buffer zones alongside the channel, taking into account the long term variations in river behaviour, form and extent, including the effects of large or more extreme flood events. Flood flow conditions become significantly different and more intense when flows are greater than around a 20 year return period frequency of recurrence, with more severe runoff and sediment generating conditions. When such floods occur, changes in the channel form and extent should be anticipated.

There are continual changes in natural channels, as the pattern and intensity of floods varies. Large flood events widen the active channel or fairway, and can cause very pronounced erosion embayments into the floodplain. A period of high flood intensity can change the channel form of unconstrained gravel-bed rivers— from single channel to semi-braided, or from semi-braided to fully braided — while a more quiescent flood regime will re-establish a narrower and less complex channel form. Thus, when drawing up river corridor boundaries, allowance should be made for the widening that occurs over periods of high flood intensity or from large events, as well as to accommodate the more regular channel migration and its erosion embayments.

The boundaries of this river corridor also provide a clear demarcation line between the land available for productive uses, infrastructure facilities and human habitation, and the river area required, given a specific management approach. The river corridor then provides for both flood capacity and the management of bank erosion and channel movement over the longer term (and hence through periods of high flood intensity). It also provides a wider and more diverse area for other objectives of river management, such as habitat, amenity, recreation and the ecological functionality of channel-floodplain exchanges.

In drawing up the boundary, account is taken of natural features, such as terrace edges, that are natural boundaries, and existing tree vegetation, as well as fixed structures and legal boundaries. The design buffer width is a minimum, and additional space, especially if covered in tree vegetation, increases security in larger events.

Management of rivers will be more effective, and less costly overall (taking account of both non-river and river management costs) when account is taken of the natural processes of the rivers, and the way in which they respond over time to natural variations and to imposed management changes. Vegetation management should also consider the natural spread of vegetation and the way in which the channel form will alter depending on the nature and extent of channel and edge vegetation.

5 MANAGEMENT PRINCIPLES

This approach to river management is most applicable to gravel-bed rivers with a wide and shallow bed where channels flow within their own alluvial material. The aim is to provide a clear river bed area where bed load is transported through scour and deposition processes, bounded by vegetation buffer zones that provide a diffuse and flexible edge to the active channel. The buffer vegetation absorbs flood flows, rather than blocking them, with the slower body of water buffering away strong currents, and thereby reducing edge pressures.

The thickness of the buffer zone means that edge vegetation can be removed, and erosion embayments formed, without management intervention. The aim is to allow natural channel movement to occur with erosion and deposition along the channel margins, and then re-establish vegetation on deposited gravel bars after channel movement or meander migration has shifted the flood flow pressure away from these areas. The buffer provides a margin of flexibility that allows vegetative management of the channel edge, with loss and re-establishment over time.

The high intensity and short duration of floods can give rise to substantial and often sharply-formed erosion embayments at the channel edges, as well as tight channel forms as deposition occurs on flood recessions. Managing the buffer edge does, then, require the cutting away of buffer areas (with re-use of the trees), as well as the re-vegetation of areas — both retreat and reclamation. Sharply hooked embayments attract erosion pressures and aggravate losses. Sharply deflecting deposits in the active channel can also have a similar aggravating effect.

To reduce edge pressures and the loss of buffer vegetation there are, then, some management interventions to realign the more severe embayments and sharp channel cross-overs, while generally allowing the natural processes of bed scour/deposition and bank erosion/accretion to take place with the least interference. This results in some reduction in channel complexity and a moderation in the variability of channel features, but reduces the management effort required over the longer term.

The emphasis in this approach to river management is on managing the buffer vegetation and re-establishing losses, as a soft edge to the river, rather than a hard fixed edge. This is less costly over the longer term, as well as being more in tune with the natural river processes. The focus is a flexible containment along the river edge or bank, with a minimum of interventions in the channel itself.

However, the clearing of vegetation from the active channel area is important. Introduced weedy species that spread rapidly along waterways have changed the vegetation characteristics of New Zealand rivers. They have given rise to rapid colonisation of the gravel areas of higher beaches or bars and islands in gravel-bed rivers. This vegetation increases channel resistance, deflects floodwaters, traps suspended silt material and reduces bed mobilisation, and hence the transport of bed material. Quiescent times in the periodicity of floods provide ideal conditions for vegetation spread, and this can change the behaviour of river reaches.

In response to these changed conditions, channel works are undertaken to clear this vegetation from gravel bed areas. Beach ripping, which disturbs the surface layer of gravel beaches/bars, can also be used to clear vegetation, while increasing bed material mobilisation. This allows bed load transport with less variability in channel form and fewer sharp cross-overs across the active channel area. Any work in flowing water, of low flow channels, is minimised, and would mainly be channel realignments associated with large erosion embayments that threaten to outflank the buffer zone. This realignment

should, though, be carried out in accordance with the size and alignment of the channels along the reach, following a natural meander curvature.

Ideally, buffer vegetation should be uniformly dense, allowing the filtering of floodwaters without creating preferential flow paths. Different species can, though, be used through the buffer width and in reserve areas, and the buffer layered with understory and shrubs, as well as taller trees. This can include native species, and nursery areas to provide source material for edge re-establishment. The buffers can, as well, be structurally strengthened to retard erosion losses and reduce the degree of encroachment in a flood event, for example by lines of cables through the vegetation held by driven piles. The river edge can be strengthened by sets of permeable groynes, and even by light rock spurs or knobs added at the edge. However, this gives rise to a more fixed edge, and these works should be understood to be temporary, as part of buffer establishment, and will require topping up or replacement after significant flood events. Once the buffer vegetation has been established these edge structural features must be removed to allow the buffer to function as a flexible edge, in accordance with the design management approach.

Composite arrangements of vegetation and structural works can be used to provide transition measures at natural controls or at artificial constraints, such as bridge crossings. For example, cable fences and permeable groynes can be used to strengthen the vegetation buffer where there is a transition from vegetative management to a solid rock lining that fixes the bank position at bridge abutments.

The clear channel and edge vegetation buffers can be applied to gravel-bed rivers that have a single channel form, provided the channel is not too entrenched. The degree to which river edge vegetation can be used to manage channel movement depends on the effectiveness of the trees in reducing flood forces along the banks, and the ability of the tree roots to hold and bind together bank material. The height of the bank and flood rise is critical in this regard.

In general, a consistent design channel or fairway based on the natural character and meander patterns of a river reach can be developed for mobile gravel-bed rivers. Maintaining clear active bed areas and margin buffer zones appropriate to a river reach reduces management efforts and generally enhance the effectiveness of management measures. The meander patterns can also guide the layout and spacing of bank protection and river training works. Thus, when repairing protection works at bends, the re-established works can be laid out to fit in with the width, radius and amplitude of natural meanders. Continuous protection works around the full length of a bend, to the curvature of a natural meander, will be more effective than works that only repair an erosion gap, and do not fit in with upstream and downstream conditions, and the overall alignment of the channel.

6 MANAGEMENT BENEFITS

The dynamic nature of river systems means that river management has to be responsive, and adjust as flood events occur and river conditions change. Any significant flood that mobilises the bed material, which is generally around the 2 year return period flood flow for single channel to semi-braided gravel-bed rivers, alters river conditions and channel form. In wider braided rivers, parts of the river bed can be mobilised during smaller events, as it depends on the size of the braids and the energy of the flow in them.

Apart from on-going programmes of maintenance of the buffer vegetation and active channel area, management effort is flood related. Repairs and reinstatement is undertaken following flood events, in response to what has occurred. The standard of protection from flooding or loss of land and assets arises from the on-going management efforts and the

space provided for the natural processes of rivers. The management effort is undertaken to provide the best initial pre-flood conditions when medium to large flood events occur. The management standard relates to these larger events, but most of the effort involves interventions after smaller events to maintain conditions that can pass the large floods, to the design requirements of the management standard. The more consistent the channel and the fewer the sharp changes in channel shape and alignment, and variations in the overall pattern, the less the flood damage and the lower the risk of erosion causing a channel breakout or direct damage to valuable land and assets in medium to large flood events.

A relatively consistent channel along a river reach, based on appropriate natural meander forms, decreases localised variations in sediment transport and flood capacity. This reduces the amount of bank erosion and flood damage, and hence the repairs and maintenance effort required to maintain protective vegetation and river works. As flood capacity, channel form and sediment transport are all inter-related, changes in one of these aspects of a river affects the others. There are, therefore, real channel management benefits from channel consistency, with less variation in the erosion and deposition activity of the river as it transports its gravel bed load, and less localised variation in flood capacity. The natural variability of rivers in the complex and highly dynamic environment of New Zealand does, though, mean that consistent reaches may be relatively short. Thus design channels or fairways can be of variable length along a river management scheme, and be of different character and width. Transitions and areas of instability around constraints, grade changes and confluences have to be taken into account in any design and management approach.

The high power but short duration of flood events in NZ rivers can give rise to tight bends and sharp cross-overs, with cusp-shaped erosion embayments, high beach/bar deposits and half-formed meanders where channels turn sharply into the bank. However, the amount of re-working of bed material and hence damage to protective measures is also limited by the short duration. Repairs and mitigation measures can then be carried out before the next event to minimise exposure or vulnerability to damage in following events. The thick vegetative buffer zones allow quick and regular responses at a low level (as in 'fix it in time before it gets worse'), and this reduces the long term costs of river management. The approach allows these smaller and less intrusive measures, while also requiring a programme of regular interventions.

A clear and consistent active channel area allows the conveyance of floodwaters and the processes of sediment transport to take place with a minimum of disruption and deflection of the river's energy. Uniformly dense vegetation buffers alongside this channel area allow some absorption and release of floodwaters while minimising damage from erosion and deposition. A thick buffer zone provides a margin area where erosion and deposition can take place. The buffer vegetation can be lost and reestablished, as channels adjust and meander along the river course, and these channel adjustments can be accommodated without threatening productive land and assets.

The buffer vegetation provides a margin of riparian vegetation that is a zone for river activity as a flexible river border, while always maintaining a riverside habitat of trees and understory.

The channel clearing ensures an active gravel bed area of adjusting channels and gravel beaches/bars and islands, and the appropriate channel widths ensure that channel migration can take place while maintaining the natural channel features, such as riffles, pools and runs. Maintaining a channel appropriate to the natural character of a reach allows a natural migration of the channel features that can form and move in a self-

maintaining way. This maintains the pattern of channel features and their aquatic habitats, while reducing erosion pressures and the need for management interventions.

This management does, though, modify the river channel and reduce the variability that could form within the active channel area. It is based on an intermediate approach between a tight control and a full withdrawal. As with any human management, there are choices based on values and priorities, while the management interventions alter what occurs along a river, in foreseen and unforeseen ways. There is an emphasis on vegetation clearance because of the effects of rapidly spreading introduced plants on New Zealand rivers. This mixed and rapidly colonising vegetation now constrains management options, while impacting on the channel conditions and sediment transporting processes of rivers.

The definition of a river corridor boundary that has a basis in the natural character of reaches, and is consistently determined along reaches, provides landowners and interested parties with a consistent management policy. All asset and land owners along and on both sides of a river are then affected on the basis of a naturally defined corridor, and all have the same information about the management approach being taken and its implications along management reaches.

7 MANAGEMENT OPTIONS & CONSTRAINTS

The implementation of a design channel or fairway and associated vegetative buffers can be undertaken at different levels of management effort, and developed over varying time periods. There are, then, management options for any given design and river corridor determination, which have a range of costs and benefits, and varying residual risks.

The vegetation of buffer zones takes time to grow and become effective, and there is likely to be a staging of buffer establishment. Structural measures and in-channel re-shaping and redirection of main flow channels may be required during the initial phases. Buffer widths can be increased to match up with natural features, and to line up with legal boundaries. This allows more space for a greater diversity of plants, including native species, to enhance the riverside environment.

The development of clear fairways and vegetation buffers has to take into consideration natural climatic cycles, and the differing effects of periods of high flood intensity and quiescent times. Intense storms or multiple storms over a short period can severely impact on catchment conditions and the supply of sediments to river systems, as well as altering reach conditions from high levels of channel activity and migration. Management practices must be responsive and adapt to these natural cycles and activities. The development of a management approach based on natural processes and providing sufficient space for river activity, cannot, then, be fully programmed, but on the contrary has to be flexible and adaptive — like rivers.

Natural constraints or control features, such as base rock exposures in the river bed, or hard banks and high cliffs at the channel edge, affect the expression of natural character along a reach, and hence the layout of design channels and implementation programmes. Reaches may be defined by natural controls, and the local channel form may be different at tight bends, where there may also be a significant change in river alignment. These control features provide a useful starting point for the development of design channels/fairways and the establishment of full width buffers.

Buffer development can take place progressively along a reach, in space and time, and this will depend on channel conditions and activity at the river edge, as well as the availability of land and access to sites. Channel clearing is carried out in an upstream direction when progressively opening up a congested channel, to provide a clear flow path downstream and minimise working in flowing water. However, the programming of clearing and other

channel works will also depend on channel conditions and areas of activity and pressure along the river edge.

Materials other than the normal bed material can be present in river channels, and this affects the implementation of design channels, and can alter development and protection measures used along a reach. For example, large boulders can be present in rivers of volcanic landscapes, as residual materials from lahar flows. These boulders alter sediment transport processes. They can, though, be rearranged for management purposes, as deliberately arranged roughness elements for channel form or to reduce flow pressure against banks, and to facilitate fish passage.

Finer sediments, derived from earlier glacial period processes, may underlie the alluvial bed material, and they can be exposed in large flood events or because of scouring around obstructions in the channel. Once exposed this finer material alters the transport of bed material and can give rise to unusually large scour depths. Bridge piers can act as obstructions, and with debris loadings give rise to deep scour holes. Bridges generally have a narrow waterway opening compared to the natural channel width at the crossing site, and are often problematic constrictions for design channels to natural channel widths.

The constriction of waterways by bridges can give rise to channel splitting and widening upstream, with a central depositional island directly above the bridge, and bed scouring at the bridge itself from flow concentration. This distortion of the sediment transport processes can have a marked effect on channel form and activity along the river reach. Substantial transition works are often required to manage flood flows and bed material transport through bridge sites.

The historical management of a river reach and the river responses to this management has to be taken into account in the drawing up of design channels and in their implementation. For example, there are many instances of rivers and streams being straightened by channel excavation and diversion works, and stopbanks constructed to confine floodwaters to main channel areas. Along the lower reaches of many of the larger rivers in NZ, river behaviour has been substantially altered by confinement, entrenchment and alterations to riverside vegetation. Channel movement and sediment transport is restricted and disrupted by these alterations. This constrains what is realistically achievable though contemporary management intervention.

The proximity of human habitation and assets to river channels, and stopbanks positioned alongside main channels, constrains river management, and the practicality of different approaches. An approach that provides sufficient space for river processes to take place with a minimum of constraint or hindrance can, thus, be in direct conflict with the human occupation and use of riverside and floodplain land.

At localities where there are valuable assets and dense human habitation close to waterways, more solid and stronger bank protection measures that fix the channel edge are used. These measures, though, compromise the edge flexibility that is an essential part of an approach to river management that seeks to work with the natural processes and behaviour of rivers. Hard rock edges, using sets of groynes or continuous bank linings, is a different approach to river management. In this case, berm land alongside the active channel is a reserve area to accommodate failure of the edge protection during large flood events, without flood defences or valuable assets being damaged or lost. This berm land may have a vegetation cover for various management objectives, but the vegetation provides no real benefit from a protection perspective.

Providing the space for a river to move and behave in its naturally characteristic way is the critical issue, and generally the most difficult to resolve. However, confining a river reach does not, in itself, change the magnitude of flood flows or the sediment and debris that is

transported to the reach. The water and sediments that come from the upstream catchment must go somewhere, and the more confined the river the greater its erosive power, as the intensity of turbulence, vortices and cross-currents increases. The more space that can be provided for rivers, the lower the likelihood of failures of protection measures and flood-retaining stopbanks.

Human activities have had, and continue to have, very substantial impacts on the landscape, markedly affecting catchment erosion and the supply of sediments and debris to river systems. Land clearance and changes in land use that decrease ground infiltration and surface detention of rainfall increase storm runoff, and change catchment responses to intense rainfalls and hence erosion and sediment movement into waterways. Conversely, the damming of rivers traps bed load, affecting the supply to the river downstream, and can alter the hydrologic regime, depending on the operating procedures of the dam.

Global climate change, as forecasted, will also increase the frequency of a given flood flow in New Zealand, and the greater frequency of intense storms will alter the response regime of catchments to storm events. Storm runoff and sediment input rates increase as rainfall intensities increase, and catchment responses significantly change from small frequent floods to medium (5 to 20 year return period) events, and even more so from medium to large flood events. The shift in the frequency of flood flows with climate change will then increase runoff rates even more than rainfall, increasing sediment supply and transport rates. This change in the regime of rivers may alter their behavioural characteristics and hence channel forms and patterns along river systems. There will be compounding effects, and the standard of flood mitigation of a given stopbank or particular flood defence measure will decline over time because of these climate change effects.

All river management measures have a protection standard, albeit not necessarily well determined or even predictable, and there will always be a flood event that can overwhelm protective defences. There is always a residual risk of flooding and flood damage, and it is only a matter of time before any protected area will be flooded.

The constraints imposed on rivers should be understood in this context. Rivers behave according to their own character, and whatever we do, rivers will respond and exert their own rules. We would do well to give rivers more room to move, and work with the forces of nature instead of trying to impose our rules and desires on rivers.

The approach of this paper is one way of working with the natural processes of rivers. It provides more space for river activity using a consistently applied methodology based on an assessment of reach character and response behaviour.

8 EXAMPLES

The management approach outlined in this paper has been applied, to differing degrees, on river reaches throughout New Zealand, ranging from small rivers with a well-defined single channel form up to wide multi-braided reaches. They have generally been rivers that flow from the main axial ranges of the North and South Island, and a list of rivers in New Zealand that I have undertaken investigations for this approach and drawn up design channels or fairways, with associated buffer zones, is given in Attachment 3.

Examples from a range of rivers and reach types are given in this Attachment. In each case, comment is given on the catchment setting, the reach character and changes over time, and the lessons learnt from successes and failures. Repeat aerial photography, generally from the earliest to the most recent, is shown for the example reaches, with the design channel and buffer zones or river corridor boundary shown on each of the repeat aerials.

These examples include reaches from the earliest applications to the most recent, and for different types of river reaches, from single channel meandering river reaches to wide fully braided reaches. The repeat aerials from the earliest available also show that the designs relate to prevailing reach conditions and alignment, and not necessarily to the earlier historical conditions. In most cases, the active channel area has been (generally) maintained to the design guidelines. However, significant changes in catchment, climatic or reach conditions would require amendments to the design guidelines. In many instances, reviews have been undertaken to re-assess the design lines and management guidelines.

9 CONCLUSIONS

River systems are dynamic and responsive, but river reaches do have specific channel forms and characteristic behaviour patterns. These reach characteristics can be determined by appropriate investigations, and guide a systematic design process that is applicable to different types of alluvial rivers. A methodology has been developed to assess reach character and draw up design channels based on this reach-specific character to guide an approach to river management that works with the characteristic behaviour of rivers.

The approach involves the determination of an appropriate channel width for the active river processes of flood conveyance and sediment transport. This width depends on the type of river reach, and whether it has a single meandering channel, multiple channels with flood overflow paths or is fully braided with many flow channels. The reach type depends on the prevailing conditions and formative influences, and this can change over time from climatic cycles or land use changes, which can give rise to a periodicity in the supply of bed material.

Vegetation buffer zones on both sides of the active channel area provide a flexible edge, which absorbs flood waters and flow pressures. The active channel area and this vegetation margin provide the space where scour and deposition processes and channel adjustment can occur with a minimum of management intervention. On going management measures work with and facilitate the river activity, through appropriate vegetation clearing and reestablishment.

The vegetation buffer zones, along with the active channel, define the management area, which is the space provided for river activity and movement. A wider river corridor provides reserve areas to accommodate changes in channel form and active channel widths, as catchment and reach conditions change over time. The outer edges of this river corridor provide a boundary line between the river and productive land uses, infrastructure facilities and human habitation. This boundary can follow existing natural features and include existing riparian vegetation. The vegetation gives rise to a continuous corridor of terrestrial and aquatic habitats, while providing reserve areas for river channel expansion during periods of high flood intensity.

The design of active channel areas and margin buffer zones has been applied to many river reaches on rivers throughout New Zealand, for reach types ranging from single channel to fully braided. The diverse and wide-ranging application of the methodology, and the successful drawing up of design channels or fairway that fit existing river courses for a range of river types, has demonstrated the applicability and usefulness of this approach.

There are, however, many constraints on the appropriate and effective application of this natural character based approach to river management. The most critical is the confinement of rivers that has already taken place, and the continual pressure to further restrict and control rivers. The proximity of human occupation and valuable assets, and a general reluctance to give up land for river purposes, pressures river management into

hard edge and rigid controlling measures. Failure can then be catastrophic, with little reserve land available to absorb the severe erosion pressures of failure conditions.

Bridge crossings and adjacent infrastructure assets have to be accommodated, and transition lengths with structural strengthening measures or edge reinforcing may be necessary to still obtain a reasonable degree of reach consistency. Natural hard points and control features also have to be taken into account, and designs drawn up that relate to the river character at these features and any change in river course they impose.

River management measures and flood defence works do not change the flood flows and sediment loads supplied to river reaches. The straightening, confinement and entrenchment of rivers, to facilitate human activities and land uses, actually increases the erosive pressures of floods and generates tight bends and acute flow angles at banks that further increase erosive pressure on river banks.

Global climate change will increase the frequency of intense storms and of any given flood flow. This will reduce the standard of existing flood defences, and increase channel activity and damage to protection measures, while increasing channel variability from flood activity within the river course. Providing more space for rivers, and managing them in a way that is in accord with their natural processes, would be a worthwhile response to the present threats from flooding and erosion hazards, and provide a greater reserve for the increasing risks from the effects on rivers of climate change.

Assessments of alternative management practices have shown that this intermediate approach is effective in reducing river management costs compared to either a tighter control over the river channel or a wider corridor with minimal intervention, while decreasing residual risks of damage to human assets in large flood events. The approach also maintains a wide diversity of aquatic and riparian habitats, while minimising the spread of rapidly colonising introduced plants within the active channel area of rivers.

The aim is to provide river management practitioners with an effective approach that is based on the natural character and behaviour of river reaches, and allows a flexible and adaptive management. This requires an understanding and experience of river behaviour in different types of reaches by the managers, and a wider space in which to move for the rivers.

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ATTACHMENT 1

RIVER TYPE PHOTOGRAPHS

MANGATAINOKA RIVER – Single Channel - Meandering

LOWER WAIMEA RIVER – Single Channel - Alternating Bars
(Banks strengthened by rock works)

LOWER OTAKI RIVER — Semi-braided, with flood overflow paths

LOWER WAIMAKARIRI RIVER — Fully Braided

ATTACHMENT 2

MEANDER WIDTHS

CHANNEL WIDTH FORMULAE

Threshold of Motion

Regime $Wr = 1.222\ Q^{0.46}/d^{0.15}$

H Chang (at Slope) $Wa = (3.10 + 0.405(\ln((0.672\ d^{1.15})/(s\ Q^{0.42})))^2)\ Q^{0.47}$

Live Bed

Lacey $Wl = 4.85\ Q^{0.5}$

Russian $Ws = 1.45\ Q^{0.5}/s^{0.2}$ I

or $Ws = 4.14/s^{0.2}\ (Q/g^{0.5})^{0.4}$ II

Where

W = meander width (m)

Q = dominant discharge (m^3/s)

s = energy slope

g = acceleration of gravity (m/s^2)

d = effective stone size of bed material (m)

CHANNEL WIDTHS for NEW ZEALAND RIVERS

A table of results given by these channel width formulae, for selected river reaches from regions throughout NZ, is given in Table 1.

CHANNEL MEANDERING within CHANNEL FAIRWAYS

Schematic diagrams of the different theoretical meander forms associated with the empirical meander formulae drawn within design fairways are given in the figures below. One is taken from the report on the original investigations of the "Upper Tukituki" scheme, and the other from the river characteristics and sedimentation report on the Hutt River, which was part of the floodplain management plan investigations for the floodplain of the Hutt River valley.

Figure from "Hutt River Floodplain Management Plan" report

RIVER CHANNEL MEANDER FORMS

The different meander forms, as they are present along the Hutt River, are indicated as representative examples on a river reach as follows:

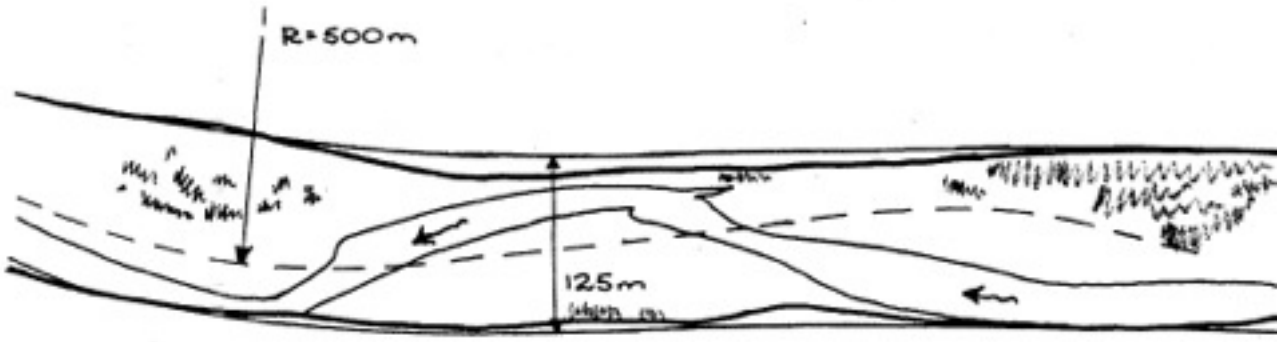
[A] Threshold of motion - minor meander
Well formed at regime slope.

Minor meanders attempting to form at the bends, but constained by high straight banks.

[B] Threshold of motion - major meander
At actual channel slope.

Low flow channel follows distorted major meander with a relatively straight form.

[C] Flow dominant [live bed]



Straight flow dominant form expressed in the limits of the overall [low flow/beach] channel.

Figure from "Upper Tukituki Scheme" report

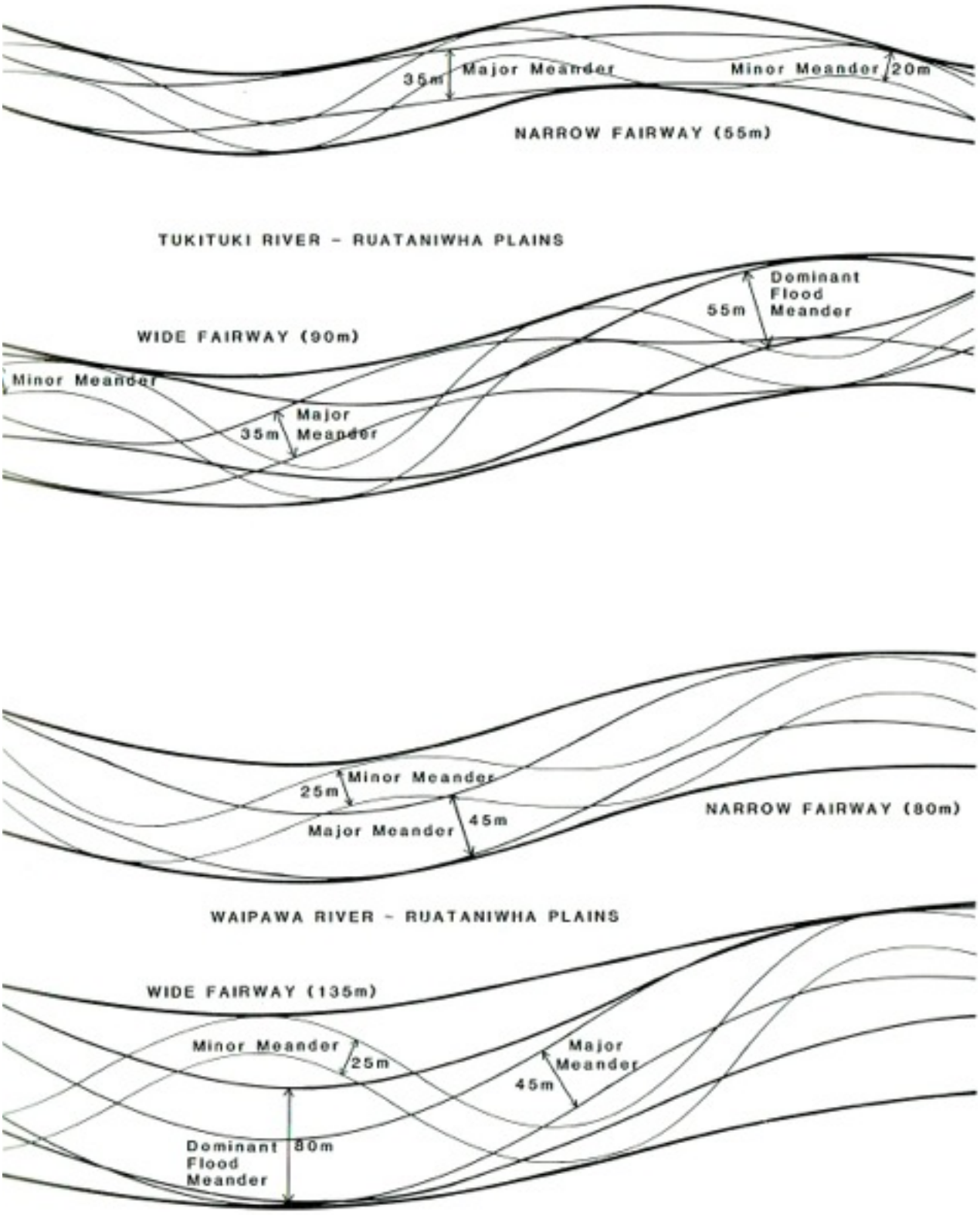


FIG. B-6
MEANDER PATTERNS
(Stylised meanders)

SUMMARY TABLES of CHANNEL WIDTH FORMULAE

The tables given below summarise the meander formulae used, design channels or fairways derived from them, and comment on the design and channel type.

They are examples of tables given in the reports on the river corridor investigations.

EXAMPLES OF APPLICATION

NATURAL CHARACTER DESIGNS

This list covers rivers in New Zealand that I have investigated for a natural character design and drawn up a design channel or fairway and associated buffer zones. The names in brackets have had designs drawn up, mainly from the study of aerials, but without investigations on catchment and reach conditions, as per the methodology outlined.

There are many other river and stream reaches where an appreciation of the type of reach and its natural character and present expression has guided design and construction.

Example reaches are given below for the river names in bold.

North Island:

Bay of Plenty — Whakatane, Waioeka, (Waimana), (Otara) (Rangitaiki), (Kaituna).

Gisborne — Karakatuwhero, (Awatere), (Waipu), (Waipaoa).

Hawke's Bay — **Ngaruroro** (lower and **middle**), Tutaekuri, Esk, **Tukituki** (lower, middle and **upper**), **Waipawa**, Mangaonuku, Tukipo, Makaretu, (Wairoa).

Taranaki — Waitara, Kakihi, (Waiwhakaiho), (Stony).

Manawatu-Whanganui — Whanganui (lower, middle and upper), Manawatu (lower and upper), Oroua, **Kiwitea**, **Pohangina**, Tamaki, **Mangatainoka**, Ohau.

Greater Wellington — Waitohu, **Otaki**, **Waikanae**, **Hutt**, Mangaroa, Wainuiomata, Waiwhetu, Waipoua, **Waingawa**, **Waiohine**, Tauherenikau, Ruamahanga (lower, middle and upper) (Kopuaranga), (Whangaehu).

South Island:

Tasman — **Waimea**/Wairoa, **Motueka** (lower and upper), Motupiko.

Marlborough — (Wairau)

West Coast — (Arnold), (Taramakau), (Waiho)

Canterbury — **Waimakariri**, **Ashburton** (**lower**, **north** and south branches), Rangitata, Waitaki.

Otago — Clutha (lower), **Kakanui/Kauru**, Pomahaka, Strath Taieri, Waianakurua, Waihemo/Shag, Cardrona, (Matukituki).

Southland — Whitestone, Weydonburn.

EXAMPLE REACHES

Examples of design channels or fairways, showing the clear active bed area and the margin vegetation buffer zones, are given below for a range of rivers and reach types. In each case, comment is given on the catchment setting and reach character, changes over time, and the application of the management approach, with lessons learnt. Sets of repeat aerial photography are shown, as attachments, for each example reach. The design channel and buffer zones or river corridor boundary are shown on each of the repeat aerials, which are generally from the earliest to the most recent available.

The repeat photography shows the changes that have occurred in the plan form of the river reaches, from natural processes and from human riverside occupation and river management activities. The designs relate to the current river alignment and active channel areas, and the application to a particular, and more managed, river condition is apparent in many of the examples.

NGARURORO RIVER [20]

The upper reaches of the Ngaruroro River cut across the main axial ranges of the North Island where they are wide and especially complex. There is a range of volcanic materials on the range land, with substantial areas of limestone formations within the uplifted greywacke of the ranges. The river rises in the Kaimanawa Mountains, and winds through gorges around the Kaiweka Range, before cutting through the main line of the axial ranges in the northern extent of the Ruahine Range. On leaving the ranges the river is deeply entrenched within a large upland plain, and develops a wide braided form where it is not constrained into a gorge.

Along its lower reaches the river crosses a large plain formed by deposition of alluvial materials within a subduction zone between limestone capped hills. The river has moved around within this plain, along with the Tutaekuri and Tukituki rivers, and the present course of the river is an artificially developed and constrained one. The gravel bed load of the river can not be transported to the sea, and the plain was naturally aggrading behind a barrier beach that is mostly formed by the coastal transport of material from the Tukituki River. Extraction of the gravel bed material is required to maintain the flood capacity of the stopbanked river, and the present form of the artificial diversion channel.

The river now flows along an edge of the plain in its upper part, but the river can flow between large outcrop hills onto the plains from this reach. The aerial photography shows this reach, which became congested and distorted by the spread of willows. The clearing of the willows and development of willow buffer zones along both sides was undertaken in accordance with a design fairway, and this was successfully implemented through a long term programme over many years.

The introduction of a willow sawfly to the Heretaunga Plains gave rise to very severe infestations, with repeat population plagues that destroyed most of the willow vegetation of the buffer zones in this reach — and elsewhere on the Plains. Mobile-bed physical modelling of a reach of the river was undertaken to develop and evaluate structural edge strengthening options. This led to the use of a mixed vegetation buffer with structural strengthening of solid groynes, but with articulating units, and pile and cabling fences.

The exposure of the land with the willow die off allowed the rapid growth of a wide range of weedy colonising species. However effective tree buffer zones have been re-established, and there has been a natural decline in the damage caused by the sawfly.

The river corridor design provided effective guidelines throughout these developments, from the initial willow clearing through to the present more diverse approach of mixed vegetation and structural measures.

TUKITUKI RIVER [18]

The Tukituki River rises in the steep and erodible Ruahine Range of the main axial ranges of the North Island, and crosses the inland plains of the Ruataniwha Plains formed behind uplifted limestone hills, before following a fault-formed valley through limestone hill

country down to the Heretaunga Plains. The remnant terraces along the range reaches of the river are evidence of cycles of deposition and entrenchment. Severe storms induce catchment erosion and high sediment input rates to the river system, with the gravel bed load then being moved downstream by regular flood events. This gives rise to waves of gravel bed load moving down the river, which may result in changes in the channel form.

A large landslide blocked the river near the bottom of the ranges in 1968. This temporarily trapped all the bed load material of the river. The loss of supply led to a change in the channel form of the river downstream, from a semi-braided pattern to a well-defined single meandering channel. When the natural dam was breached and the accumulated sediments released, an opposite change occurred back to a semi-braided to braided form, as the gravel bed material moved into the downstream reach. These changes in channel form diminished down the river, with much less marked changes apparent along the Ruataniwha Plains reach.

The Tukituki River, and other rivers that cross the Ruataniwha Plains, have naturally migrated across the plains, with channels developing, aggrading and then breaking out into new channels. Older river courses are clearly visible in the plains topography.

Various stopbank flood mitigation measures have been built and re-built over time along the plains reach, while willows planted to reduce bank erosion have spread over the river channel. This vegetation spread had given rise to a partially blocked channel, with a complex variable form. A design fairway and buffer zones was determined to guide substantial channel clearing, widening and realignment to give a consistent width of active channel area. The willow vegetation was re-developed to give dense buffer zones on each side of the active channel area. At the same time, the stopbanks were raised and re-levelled, with secondary defence banks added as overlapping wing banks to act as a backup flood defence in case of river break-outs.

The aerial photography shows a part of the plains reach where the river is naturally unconfined, and where a design fairway and vegetation buffers has been fully developed.

A programme of mechanical raking of beaches/bars (dry gravel areas during low flows) was implemented to reduce vegetation colonisation and increase the mobility of the gravel bed material. This reduced the sharpness of channel cross-overs and the degree of channel section variability. It requires extensive machinery work, but the cost is not a large proportion of the maintenance budget, and it has been very effective in reducing flood flow pressure into the buffer zones, and hence buffer vegetation losses. The rapid spread of introduced weedy species and the infrequency of mobilising flood events means that such a measure can be cost effective, especially when the channel edge is managed by vegetation alone.

The design river corridor and management regime have maintained a relatively clear gravel-bed channel, while a programme of planting and re-establishment of the buffer vegetation has contained edge erosion and very much reduced the risk of channel breakouts onto the plains. This has been done without any use of structural measures or the fixing of the river edge by hard engineering works.

WAIPAWA RIVER [18]

The Waipawa River has a similar catchment in the Ruahine Range as the Tukituki River, and a similar channel form and character across the Ruataniwha plains. It has, though, a larger range catchment, and carries a larger gravel bed load. The channel aggradation rate along the plains reach is thus greater, and over a wider and more braided active channel.

The older courses evident on the plains also indicate a trend of channel migration to the south, from a fault movement tilting of the plains.

The design fairway and river corridor is thus similar to that for the Tukituki River, and was implemented in the same way. More extensive works were required for this wider and more powerful river. However, a relatively clear fairway edged by continuous buffer zones has been developed and maintained, without the use of rock works or other structural measures. Aggradation within the now-defined river corridor remains an issue, and this can be managed by well-directed extraction of the bed material. Suspended load silt and sand material does build up in the wide buffer and reserve areas between the stopbanks.

The aerial photography shows a part of the plains reach of the river.

KIWITEA STREAM [36]

The Kiwitea Stream rises in a steep dissected landscape formed in uplifted marine surfaces, and then flows down a sloping inland plain to the Oroua River. Below this confluence, the Oroua River flows across the flat Manawatu Plains to the Manawatu River. The marine deposits include layers of sand that are easily eroded and then transported into and along the waterways. Along its lower reaches the stream has a single channel form, with gravel beaches, and the meandering channel wanders across the wide area of plains. The stream is edged with tree vegetation of variable width, density and tree species.

Management of the stream was undertaken as part of a broader scheme, but at a low level of intervention, and mostly relating to the edge vegetation. A design channel was drawn up to guide this management and to develop more consistent, if thin, buffer zones along the full scheme length of the stream.

Little had changed prior to a very large flood event that occurred in February 2004, when an intense storm affected a wide area, including most of the Manawatu River catchment. The flood severely affected the stream, with bank erosion removing much of the edge vegetation and substantially widening the stream bed, with large erosion embayments being formed. The flood effects were so severe that the stream character and channel form was completely altered.

The design channel, which was based on the stream character as generated by the more frequent flood events, was then used to re-develop a channel that suited this flood regime and its associated channel form. Remedial measures could be guided by the design channel, with the large embayments being reclaimed and the active channel width reduced and realigned to that of its more usual pattern.

The channel re-forming was then undertaken to an appropriate pattern, consistently applied along the stream, with the channel curvature and meandering of a natural channel form. Structural measures, mainly pile and cable fences and some rock works, were used to reclaim large areas of erosion and deposition.

In response to the massive damage, the works undertaken were probably more than necessary, and there could have been more reliance on the natural reforming processes of the stream channel. A reasonably well defined channel has though developed over time, with a more consistent pattern than prior to the flood event. However, there are still areas of instability, and more recent flood events have eroded out further large embayments.

The aerial photography shows the lower end of the river, from just upstream of its confluence.

POHANGINA RIVER

The Pohangina River flows down the western side of the Ruahine Range, with tributaries from the range on one side and from a steep dissected landscape formed in uplifted marine surfaces on the other. The different geology of the two halves of the catchment gives rise to a mixed sediment input, with greywacke gravel material coming from the range tributaries. The river is confined by the steep landscape and terraces alongside the river, and has only a narrow floodplain area along its lower reaches. The river character changes along its lengths because of variations in confinement and sediment input from its tributaries.

The channel form thus varies from a single thread meandering form, to semi-braided or a split channel form, with quite long relatively straight reaches. There is generally a band of vegetation along the river, and the scheme management of the river channel is mostly repairs and re-establishment of this edge vegetation. During more intense floods, and where there is a relative accumulation of gravel bed material, the river channel will develop a more split or semi-braided form, and can break through the confining edge vegetation to form long parallel channels around the vegetation. Management efforts have been directed at suppressing the semi-braiding response of the river, and following break outs, to re-instate a single thread channel.

A river corridor design was drawn up in 2001, as part of a scheme review. Given the natural variations in river character and the effects of past management, the design included three different channel forms along different reaches of the river. River management measures were guided by these design channels or fairways. However, the edge buffer zones remained relatively thin, and channel break-outs remained an on-going hazard.

Severe floods in the Pohangina River in 2004 brought about extensive channel widening, large erosion embayments, bed aggradation, and break-outs onto the floodplain. The design river corridor provided a template for remedial and re-instatement measures, but there was continual damage to the structural works used to reconstruct bank edges. Break-outs were blocked off and channel re-shaping undertaken along with vegetation re-establishment. Some rock works were implemented at critical places, to protect major assets, such as bridges. However, river management has been especially problematic since the floods, and there remain inconsistencies of width and meander pattern along reaches, with some large erosion embayments and areas of channel instability. The long length of river with a narrow floodplain makes it difficult to fund protection works on this river.

The aerial photography shows the lower end of the river, from just upstream of its confluence.

MANGATAINOKA RIVER [38]

The Mangatainoka River rises in the northern end of the Tararua range, but has a very small range catchment area, and flows down a broad valley formed between fault lines, with terrace formations along the valley. The river has a relatively steep grade down the infill valley, with sediment transport defined more by the re-working of the alluvial deposits of the valley floor than supply from the upper catchment. The river has a single channel meandering form that is very mobile as it moves around the flat floodplain of the valley. The bed of the river has a thin layer of alluvial gravel over base rock.

The tight loops of the meandering channel and the rapid movement at bends makes management of the river unusually difficult. A range of management approaches, with various river corridor setback arrangements, has been investigated and tried out over

recent decades. The use of weirs across the active channel is a feature of this river management, with the weirs being located upstream and downstream of bends. The margin vegetation is very thin, and the entrenchment of the channel makes it prone to under scour loss.

There have been a number of medium to large flood events in this river since 2000. In response, design channels were first drawn up for short reaches of the river, and a set of management measures determined for these reaches. Later a design channel was drawn up for the full valley length of the river.

The tightness of the channel meandering and the distorting and deflecting effects of both valley side bluffs and base rock controls in the bed, plus the large number of road and rail bridge crossings of the river, meant that the design channel was relatively variable in its alignment and curvature. However, a consistent channel with natural meander curvatures could be fitted to the existing river, and this design has been used to guide bank protection and flood damage repair works.

The river management scheme has been through a number of reviews over the years. Funding the protection and repair works has always been difficult, given the extent of the scheme, the relatively narrow valley flats at risk and pastoral grazing use of the land. The design does mean that the works that are undertaken are aligned to the meander curvatures of the river. The mobility of the river does, though, give rise to channel compression against solid protection works around bends and to protect bridges. The weirs are also fixed features in the river. At the same time, a vegetation buffer is not that effective in retarding the meander migration of the well-defined but mobile single channel of the river, whatever its density or thickness.

The aerial photography shows a length of the river in its middle reaches.

OTAKI RIVER [30]

The Otaki River rises in the very steep land of the Tararua Range at the main divide, and the catchment is mostly rugged forest-covered range land. Severe storms in 1936 and 1955 caused widespread slipping and damage to the forest cover. Sediment input to the river system increased substantially after these events. The lower reaches cross a narrow coastal plain that consists of glacial period outwash materials with sandhill formations near the coast. The present river channel has degraded into these deposits, with high gravel terraces bounding the floodplain downstream of the foothills. The river carries gravel bed material through to the coast, but there is a natural deposition of some of the bed material near to the coast, where the river grade decreases, with the river crossing a fault line.

The lower reaches naturally have a semi-braided active channel with flood overflow paths, to below the fault line, where the river splits and migrates within a flat floodplain that extends through the sandhills along the coast. This lower reach, below the SH 1 Bridge, has been straightened and confined by stopbanks alongside the formed channel. The design channel for this reach is a very straight form of a live-bed or dominant flow channel. There is little space for buffer vegetation, and there has been a progressive increase in the use of rock works, with linings being added and extended over time.

The bend at the fault line became increasingly tight over time due to continual reinforcing of the outer bank of the bend. As an alternative to this bank reinforcing, a channel diversion was undertaken to realign the bend to a more natural curvature and with a greater channel width. Upstream of this bend a narrow reach of the river was widened, and the stopbank set back. These works allowed a wider fairway to be drawn up for the upper part of the coastal plains reach of the river.

The aerial photography shows the reach from the fault line bend to above the area of channel widening.

The lower reach below SH 1 is problematic because of the past straightening and confinement. While an alternating main channel does form around gravel bars, there is insufficient space for appropriate buffers or for any channel widening in large flood events.

Above SH 1 a clear fairway has been developed to a consistent width that allows channel meandering, and substantial buffer zones have been established that allow an effective use of this vegetation. However, the coarse bed material and intense short duration floods of the river means that complex channel forms do arise in the fairway, and channel re-shaping and re-alignments continue to be undertaken. The more intense channel works are undertaken to reduce the erosion risk to high terrace cliffs.

WAIKANAE RIVER [28]

The Waikanae River rises in the lower range land of the Tararua Range, and a number of tributaries come together within an inland basin area of hills and terrace land, before passing through uplifted coastal hills. The lower reaches then flow across a depositional fan and through sandhills to the sea. There were two distinct channels across the fan, but one was cut off and the other developed into a well-defined channel. Over time, river management has given rise to a meandering channel of nearly constant width, with the river having a single channel form with a low flow channel around alternating bars.

All the gravel bed material of the river is deposited in the fan area, and there is a natural aggradation trend along the lower reaches, down to a short estuarine reach. The present river channel tends to migrate as a whole along this fan area. The design channel fixes a particular position, but does have a meander curvature that is appropriate to its single channel form. The design channel width is thus based on the characteristic threshold of motion meanders of the river, throughout the scheme length.

A mix of management measures has been used to suit local site conditions and the channel alignment. As well as the vegetation buffers, measures include permeable groyne sets, solid rock groynes around bends, rock linings and rock weirs across the channel.

The aerial photography shows the reach below the SH 1 bridge along the upper part of the fan.

A well-defined channel has been maintained through a flood regime that included medium to large flood events, with relatively little damage, and without any significant channel realignment or break outs. The relatively low stream power and small gravel bed load means that the river can be managed to a single channel form using standard NZ measures of vegetation and structural works.

Repeat cross section surveys of the active river channel suggest that the development of a constant width well-aligned channel may be increasing the throughput of the bed material down to the estuarine reach. Bed material deposition will, though, continue along the fan area of the river.

HUTT RIVER [25]

The Hutt River rises in the southern end of the Tararua Range, and flows south down a fault split landscape of tilted blocks. The lower reaches follow the Wellington Fault, where buckling has given rise to substantial basins that have been infilled with alluvial materials. Where the river leaves the fault line to flow into Wellington Harbour, there is a major

change in river grade, and bed material deposition naturally takes place around the grade change, and at the river mouth.

The catchment is mostly rugged forest-covered range land and the present supply of gravel bed material is relatively small. The lower reaches through the basins of the Hutt Valley have been entrenched by a river management approach of channel straightening through gravel extraction from the bed, straight channel cuts and continual reshaping of the bed following flood events. The river now has a single channel form with a low flow channel around alternating bars, and an unusually coarse bed material. The straightness of the river course means that the main flow channel cannot develop fully formed meanders, and there is a pattern of half-formed meanders with very sharp cross-overs. There is a direct attack to the bank at the cross-overs, with a deep and narrow scour hole along the bank downstream.

Vegetation buffer zones have been established along the channel edge. However the height of the gravel banks makes vegetation relatively ineffective in this case. Thus, rock linings, or sets of rock groynes have been constructed progressively over time, mostly along the outer bank of meanders. Downstream translation of meanders has led to incremental extensions of rock linings over time, while other lining lengths become redundant.

The aerial photography shows the reach in the Lower Hutt Valley, from the start of the grade transition and bed load deposition reach.

A riverside park has been developed along the Hutt River, and urban development, including recreational parks and golf courses, has resulted in a constrained river channel. This has reduced river management options, although the river corridor does include the riverside recreational areas.

The Hutt Valley is now fully urbanised, and river management must consider a range of objectives, which are not all compatible. While vegetation has been used as much a possible, for environmental and economic reasons, the river condition and close proximity of flood defences protecting urban areas severely constrains a flexible approach to river management. The river channel entrenchment and lack of unused space along the river also prevents the adoption of a more resilient approach to river management that allows for the natural movement of the river channel.

An understanding of the natural character of the present constrained river and its response behaviour can, though, guide the layout and construction methodology of works, to give better outcomes environmentally, as well as being economically more effective.

WAINGAWA RIVER [21, 45]

The Waingawa River rises in the central part of the Tararua Range at the main divide, and the catchment is all within this very steep and rugged forest-covered range land. The river system follows the main fault lines and cross-faults of the block displaced landscape, and large slips extend up the steep valley sides. The lower reaches cross the wide Wairarapa Valley at a relatively steep grade down to the Ruamahanga River on the other side of the valley. Across the plains, the river has a very narrow floodplain, with no tributary inflows. The active West Wairarapa Fault follows along the edge of the range land, and movement of this fault affects the position and grade of the river where it enters the valley.

The river follows a relatively direct path across the plains, but is affected by fault lines within the valley and remnant terraces from fault movements and the long-term degradation trend of the valley rivers. The coarse bed material and the rapid spread of introduced plants gives rise to channel splitting and the build up of islands. The channel

then tends to become perched in places with the potential for breakouts to one side or the other, into the narrow floodplain area alongside the river.

The lower reaches show a marked change in channel form as the flood intensity varies over time, from a meandering channel split around large islands in quiescent periods, to a wider active channel area with a semi-braided form in periods of high flood intensity.

A wider fairway design has been applied to the lower reaches. The aerial photograph shows a mid-plains reach, where there is a tendency for the river to deposit bed material and widen its overall channel.

The establishment of buffer zones has been slow and intermittent along the river, but a relatively clear fairway has been developed and maintained. This has required continual channel works, including channel re-alignments and repeated re-direction of main flow channels at areas of edge attack.

There has not been a sufficient development of buffer zones to allow a less interventionist approach to river management, and funding constraints have prevented the adoption of a different approach.

WAIOHINE RIVER [21]

The Waiohine River has a very similar range catchment to the Waingawa River, and its entry to the Wairarapa Valley is similarly affected by movements of the West Wairarapa Fault. The Waiohine River is, however, substantially entrenched into the plains below the ranges, and bounded by high terraces. The river then flows across the plains and can move across a wide fan area as channel build up and breakouts occur. There is a major reduction in river grade, and consequential change in channel form, around the area of the SH 2 Bridge.

The channel below the bridge was an existing channel when river management commenced, and channel loops have been cut off, and the channel stabilised by on-going management measures. The channel is now relatively consistent in width and meander pattern, with edge vegetation and structural measures along the banks, although there are high banks that are difficult to protect.

Above the bridge the river has a shallower and wider channel, which would naturally be semi-braided with flood overflow and breakout paths. The town of Greytown is at risk from this reach of the river, and it has been more intensively managed over a long period of time.

A wider fairway design has been applied to the lower reaches above the SH 2 Bridge, and the aerial photography shows the reach above Greytown. The river had been especially narrowed and constrained at the Kuratawhiti Street/River Road crossing. This narrows has been removed, although there are still on-going effects from the past channel variations in width and form.

The river tends to form large erosion embayment in flood events, which create a more sinuous meander pattern. Over time these embayments have been reclaimed, and more continuous and wider buffer zones established. However, there have been continual channel interventions, with long straight re-alignments being formed. Some entrenchment of the channel, because of its constant artificial re-working and containment, has increased bank heights. This has improved the flood capacity of the river channel, but reduced the effectiveness of the edge vegetation and adversely affected vegetation reestablishment.

WAIMEA RIVER [47]

The Waimea River crosses the Waimea Plains, and has two main tributaries, the Wairoa River to the south-east, which flows from the Richmond Range through steep range land, and the Wai-iti River to the south-west, which flows through the Moutere Gravel hill country.

The Waimea and lower Wai-iti Rivers flow through an alluvial plain of recent gravel deposits that is bounded by older Quaternary gravels. The plains lengths of the rivers, including the Wairoa River, have been significantly entrenched by past extraction of gravel bed material. They have also been confined and straightened, and high rock linings have been placed along the outer erosion side of bends to contain erosion. There is, though, a narrow band of edge vegetation along most of the plains length of the Waimea and Wairoa Rivers.

The rivers have a relatively coarse gravel bed material, and the entrenchment and upstream back cutting of the rivers would have given rise to a coarsening of the bed material. The upper plains reach of the Wairoa River is especially coarse. The lack of finer gravels and sand would reduce bed material transport rates, and increase the sharpness of channel forms generated on the recession of flood events.

The Waimea Plains are intensively used, with large areas in horticulture, and with urban and industrial areas. The Waimea and Wairoa Rivers have continuous stopbanks on both banks along the plains reaches, and there is a relatively narrow berm between the channel edge and the stopbanks. The river channels are kept clear of vegetation, and the banks are maintained using both vegetative techniques and rock works.

A fairway based on the flow dominant meander form of the river has been drawn up for the Waimea River down to where the river grade reduces as the river adjusts to the sea level control at its mouth. A threshold of motion design channel has been drawn up for the short transition reach to the estuary. The river channel has an alternating bar pattern, with some regularity to the low flow channel meandering, but the channel form is relatively mobile, with some channel splitting. The design fairway fits this channel but is quite straight, with a low sinuosity.

The aerial photography shows the reach upstream of the grade transition.

The design provides a guideline for the alignment and curvature of bank protection measures, and for their overall connectivity along the river in relation to the channel form.

UPPER MOTUEKA RIVER [47]

The Motueka River rises in the steep range land of the Richmond Range, which consists of old sedimentary rocks and intrusive volcanic rocks in the Red Hill area. This range headwaters is a small part of the Motueka catchment, and the upper Motueka River flows down a wide straight infilled valley of old Quaternary gravels, within the dissected Moutere Gravel hill country.

There is a relatively low supply of gravel bed material from the headwater ranges, with a re-working of old Quaternary gravels along the valley of the upper Motueka River. There is little recent deposition (of the present inter-glacial Holocene period) along this river valley, and the river would have a degradation trend under the present climatic regime. Substantial volumes of bed material have been removed over many years by gravel extraction operations, and comparisons of repeat river cross section surveys show that the river channel has degraded in proportion to this extraction.

The upper Motueka River valley has been cleared for farming, and the vegetation alongside the river is made up of introduced species, especially willows. There has been river management activity over a long period of time, with on-going efforts to develop a defined clear channel or river fairway and vegetation buffer zones on both sides of this channel. The channel and margin vegetation, though, remain variable in extent and definition, and lack continuity and consistent thickness.

A design fairway has been drawn up that suits the existing river channel form, variability and alignment. The development of this river channel would, though, involve significant realignments and both vegetation clearance and establishment. The past management has contained and re-directed the river channel, but the river does not have a consistent meander pattern, and there is considerable variability in form and alignment, with some sharp cross-overs and tight bends.

The design, then, provides an overall objective and general guidelines on channel form for the river management that is being undertaken along the upper Motueka River.

WAIMAKARIRI RIVER [41]

The Waimakariri River and its main tributaries rise in the Southern Alps at the main divide. The river has a large mountainous catchment, with inland basins and gorges. From the lower gorge through the foothills ranges, the Waimakariri River crosses the wide Canterbury Plains. Over geological time the plains have built up from fluvial deposits derived from erosion in the Southern Alps, with several phases of extension or progradation during the cold glacial periods of the last 2 million years (Pleistocene period), when sea levels were lower. During the warmer inter-glacial periods (as at present), there has been a trend of incision or entrenchment, with terrace development in the upper plains, and deposition with further extension of the lower plains to a higher sea level.

Prior to containment by stopbanks and river works, the Waimakariri River had a very extensive floodplain along its lower reaches, with river channels and flood waters spreading out to both sides of Banks Peninsular, from north of Kaiapoi to Lake Ellesmere (Waihora), just north of the Rakaia River.

The plains reach of the Waimakariri River can, then, be divided into sections of significantly different natural character.

- ★ The upper reach, below the gorges, is entrenched into the plains and contained by terraces, which progressively reduce in height down the river. The river is relatively steep, and has a wide fully braided channel of coarse to fine gravel and sand. The gravel bed material is transported through this reach, with the river obtaining additional bed load from the terrace faces when they are undermined by river attack.
- ★ A transition reach where the river grade reduces (to accommodate the present sea level), and where there is now a confined fan development with a channel break out trend. Here the river bed intersects the surface of the plains, and the river can escape the confinement of the upstream terrace system.
- ★ The lower aggrading reach, where the river breaks up naturally into many different channels, as it crosses a depositional plain to the sea. The confinement of the river has given rise to an accumulation of gravel bed material within the river channel, with all the gravel material transported down the river being deposited in this reach.
- ★ A prograding reach at the sea, where sand material is deposited, and lagoons form within the tidal zone.

For the upper entrenched reach, where the river has a fully braided channel form, the nature of the river has not been altered by stopbank confinement or river works. However, introduced plants have changed the vegetation dynamic along the reach, with various fast growing colonising species now present in the river channel. Vegetation buffer zones have also been established along the edge of the river channel, and alongside the terrace faces, using mainly willows. The aim of this buffer zone planting has been to reduce erosion attack to the terraces (and hence reduce the amount of gravel material introduced into the river from the terraces) and to protect farm land from erosion (due to changes in course).

Vegetation buffers have also been established along the lower plain reach, but the channel edge is mostly defined by large rock groynes. The erosion embayments around the groynes direct strong erosive forces on to the groyne banks, especially on to the upstream side, and deep local scour holes are formed at the groyne heads. This affects the development of braids, and especially the larger braids that form over relatively long distances. The vegetation between the groynes is, then, really a back-up to suppress the erosion embayment activity, and does not really give rise to a diffuse and moveable edge to the river channel as flood intensity and braid activity varies over time.

A wide river corridor is managed as public land with vegetation buffers being established, along with the rock works. Design fairways and channels were drawn up to provide guideline boundaries for the planting programme. The aim was to determine a consistent width for each of the distinctly different reaches, to reduce the sideways pressure from channel or braid belt splitting. For much of the river course across the plains the river has a wide fully braided form. A very wide fairway was then drawn up based on a study of braiding patterns and the formation and movement of belts of braids, which are a composite of braids that migrate together.

Extensive vegetation buffers have been established along the river course, as a wide flexible vegetative margin and as infill between and behind rock works.

The aerial photography shows a fully braided reach of the Waimakariri River, where it transitions from its confinement by terraces to the lower depositional reaches.

ASHBURTON RIVER [42]

The Ashburton River rises in range land behind the Canterbury Plains, and crosses the plains between the Rakaia and Rangitata rivers, which extend back into the Southern Alps. The river forks into two main branches upstream of the town of Ashburton, and the river channels across the plains are managed, through a community scheme, including the upper plains tributaries of Taylors, Bowyers and Pudding Hill streams. The catchment across the plains is relatively narrow, being less than 10 km wide along the lower 40 km. The Canterbury Plains have been formed by glacial outwash and alluvial deposits, and wide fans have formed beside the rivers crossing the plains. The fans of the North and South branches of the Ashburton River merge into the much larger fans of the mountain fed rivers of the Rakaia to the north and the Rangitata to the south.

There are important differences in channel processes across the plains, affecting channel form, sediment transport and flood or channel break out potential. Along the Ashburton River system there are three main segments of significantly different natural character.

- ★ The upper reaches, where the rivers and streams are entrenched into the plains and contained by terraces. These terraces progressively reduce in height down the plains, and become more intermittent in form.
- ★ The mid reaches, where there are more complex changes in terrace containment, channel incision and river grade. Along the South Branch there is a well defined

terrace along the northern side, to about Blacks Road, where the stopbanks begin. Along the southern side containment of the river is less well defined, but flood waters generally follow the river course. On the North Branch there is a major change in grade, where the natural tendency of the river is to split up and break out into different courses. Confinement of the river to a narrow fairway, with flood containing stopbanks, has given rise to substantial channel aggradation from the build up of the gravel bed material. Generally, there is a tendency towards a split channel form with channel break outs and changes in course along this transition zone. There is, though, some terrace development with intermittent terraces and channel incision.

- ★ The lower entrenched and degrading reach of the main stem, where the river grade steepens again and terraces re-develop, with increasing height in the downstream direction.

The main aim of the river management is to reduce flooding and the risks of channel break outs. Stopbanks have been constructed along the main stem, below the confluence of the South and North branches, along the North Branch and along the northern side of the South Branch. Channel fairways, defined by vegetation buffer zones have been developed along all the scheme reaches. Management is aimed at keeping the fairways clear of vegetation, while maintaining the edge vegetation as a buffer against erosion, channel break outs and flood overflows.

Past river management, before the present scheme as well as through the scheme, has substantially altered the river channels. Tree vegetation, mostly willows and poplars, has been used to contain the rivers and narrow the river channels. Other introduced plants have changed the vegetation dynamic within the river channels, with various fast growing colonising species now being present. Substantial areas alongside the river channels were planted under the development phases of the scheme, especially where the aim was to narrow the river channel. There are now continuous vegetation buffer zones throughout the scheme, but they vary greatly in width, as well as vegetative density and vigour. The protection vegetation is being adversely affected by weed species, especially vines and creepers, such as the introduced Old Mans Beard (Clematis vitalba), and diseases. The smothering by Old Mans Beard is particularly severe in the lower reaches of the Ashburton River, including the lower South Branch.

Design channel and fairway widths, for the different regime conditions, were determined for the South and North branches of the Ashburton River and its main stem, to provide consistent management guidelines that are related to the river reach conditions.

The design river corridor fitted into the existing channel and vegetation buffer areas, and a consistent meandering could be achieved, with very few exceptions. The main variation to fit the existing conditions and river course was in the amplitude of meandering.

The aerial photography shows a reach of the main stem of the Ashburton River below the South and North Branch confluence, passed the town of Ashburton, and a reach of the North Branch along its confined length across the plains.

KAKANUI & KAURU RIVERS [48]

The Kakanui River and its main tributary the Kauru River rise in the Kakanui Mountains. This range land is deeply dissected with narrow gorges, especially in the lower range land. The Kakanui Mountains is mostly schist, of varying ages and foliation, but with a capping layer at the higher elevations of basaltic volcanic rock. There is some sedimentary rock along the lower range land, as well as the rolling hill country, while the plains are mostly

covered in older alluvial of the Pleistocene, with some recent alluvial of the present interglacial.

The river bed material is then derived from a small proportion of hard basalt and mostly schist material that is quickly broken down, especially because of abrasion from the basaltic stones. The river channels in the range land have much exposed baserock with small gravel bars. The catchment supply is, thus, relatively small, and would be very episodic, depending on the more extreme storms and flood flows, and follow on transportation along the rocky river channels.

The alluvial plains have been built up from material supplied from the southern high land, and there is a high terrace along the northern side of the plains reach of the Kakanui River, from land tilting and uplift. The baserock is also very close to the surface along this northern extent of the plains, with frequent exposures in the river channel. There are terrace formations on the plains, with some loess cover, and the terraces alongside the lower Kauru River indicate a long-term cutting down during the present interglacial period.

The Kauru River has a rapidly changing form along its short plains reach, from a single meandering channel, to wandering and semi-braided, to a wide area of channel activity with channel splitting and braid migration. This is despite a constant grade and no tributary inflows. The channel becomes wider and shallow, with low banks, and channel splitting and breakouts would occur naturally, especially along the lower reach.

The Kakanui River does not have the same apparent supply of bed material to the plains, but it may just be more episodic, due to the constrained and complex channel it has above the plains, where there are definitely localised deposition and re-working areas. The slight steepening of grade below the Kauru confluence likely reflects bed material deposition at this confluence. The Kakanui River then flows along one edge of the alluvial plain, beside a high terrace, where it has a semi-braided to wandering partly split channel form. There is another deposition reach mid way down the plains, with a change in grade as the river flows away from its northern (terrace) constraint and across its flatter lower plains, down to the coast. Along this lower reach the river has a single channel form winding across the plain down to a short estuarine reach.

Different design channels and fairways have been drawn up, which reflect the varying river types and conditions of the lower reaches of the rivers. The complex landscape and varying river characteristics are then reflected in the different designs, but together they form a connected river course that takes account of the natural transitions and controls over the river form.

The aerial photography shows a reach of the Kakanui River below the Kauru River confluence.