Towards Strategic Gravel Management

Gravel plays an important role in the health of Southland's Rivers and has a role in Environment Southland's flood management. It is also an important resource for the region's infrastructure development and maintenance. How and why gravel is managed continues to come under some scrutiny. Environment Southland are in the process of updating its gravel management approach to ensure it better aligns with all regional outcomes.

Towards Strategic Gravel Management is a technical working report to inform the discussion on Southland's gravel management approach. It 'outlines a series of scientifically led strategic principles and recommendations that should underpin and inform gravel management in Southland's rivers'.

The document is a geomorphological perspective. Over time this report will become one of several documents that will provide fundamental understanding and possible methods for Southland's gravel management.

The report makes several suggestions, upon which Environment Southland has already made some progress:

Recommendation	**Environment Southland (ES) action**
The need for reliable information on the gravel load of Southland's rivers to create gravel budgets.	Data gathering for gravel budgets is underway. Additional funding is needed and has been requested through the 2024/24 Long-Term Plan.
The need for a holistic approach to gravel management.	ES is transitioning work to have an integrated catchment focus in accordance with our proposed Southland Water and Land Plan.
Further studies on how channels respond to vegetation lock-up in Southland and further trials assess the viability of using gravel management options that intended to 'unlock' channels include bar top (beach) skimming.	The report highlights several trials already carried out by ES. Further trials are being planned, including a focus on ecological values.
In the long-term, allowing the river room to erode will increase the geomorphic and habitat diversity in the river corridor and improves resilience in the face of increased flood magnitudes.	Floodplain management will create the opportunity to explore options for giving the river more 'room to move'.
A collaborative approach to problem-solving.	In early 2024 ES will invite a Gravel Working Group to recommend steps towards strategic gravel management.
A phased approach is needed, and communities will need time to appreciate and understand the changes in practice.	Staged approaches are being planned for both freshwater management and the floodplain management plans. Community engagement is fundamental to this approach, and ES is committed to working with the community to identify and implement solutions.

Environment Southland look forward to hearing from you regarding this discussion document and the future of gravel management. Please direct feedback and questions to Ella Lawton, ella.lawton@es.govt.nz

Towards Strategic Gravel Management

Working Report to Environment Southland

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Version 1: December 2023

Executive Summary

This document outlines a series of scientifically-led strategic principles and recommendations that should underpin and inform gravel management in Southland's rivers. These principles and recommendations are outlined in this executive summary.

Principles

Where a reach of river sits within its catchment must be taken into account when assessing its characteristics, behaviour and likely trajectory to inform gravel management, because rivers act as 'sediment conveyors' in their catchment. The sediment conveyor is not smooth, but jerky, which means sediment is conveyed often as a series of steps, resulting in progressive waves of gravel moving through a river, mobilised during flood flows. Furthermore, a catchment can be classified in terms of sediment 'production', 'transfer' and 'depositional' zones.

Critical to gravel management in Southland rivers is understanding the flux of gravel in these systems. The delivery of gravel to the channel varies over time and the conveyance of gravel along the active channel will fluctuate as flood magnitudes and frequencies fluctuate and gravel is pulsed through the system in a series of bed waves / gravel slugs / gravel sheets. An effective gravel management strategy must, therefore, be predicated on reliable information on the gravel load of Southland's rivers. A quantified gravel budget is needed to understand whether gravel extraction is appropriate, sustainable, or likely to result in damage to the river corridor.

Recommendations

An holistic approach to quantifying gravel budgets should be utilised using survey approaches that generate topographic data from the active river channel (wet and dry) to generate a continuous surface visualised as a Digital Elevation Model (DEM). Differencing a surface (DEM) from one time to another generates a DEM of difference (DoD), from which volumetric change in gravel over time is determined and linked with morphological changes in the river channel. Bathymetric LiDAR is the most appropriate tool to acquire information of a sufficient resolution and accuracy, and at an appropriate scale in order to generate meaningful gravel budgets in Southland rivers.

A key problem identified by ES staff is the increasing vegetation colonising active channels of hitherto bare gravelly surfaces. This situation likely arises from a period of smaller floods, which drape fine sediment across bar surfaces without mobilising gravels. This has the effect of both increasing embeddedness of the gravels in these surfaces and providing substrate more suited for vegetation to colonise. The overall effect is to reduce mobility of sediment stored in these vegetated / vegetating bars. Furthermore, once colonised by vegetation, root mats and stems further increase resistance to flows, limiting gravel mobilisation to events that are sufficiently competent to strip vegetation and fine overburden, which tend to be limited to large flood events (magnitude and / or duration). Meanwhile, unable to entrain and replenish sediment from bars within the active channel, the river may respond by incising its bed and / or undercutting banks. Precisely how channels respond to vegetation lock-up is yet to be fully quantified in Southland and studies addressing this issue should be considered.

Gravel management options intended to 'unlock' channels include bar top (beach) skimming; trials should assess the viability of this approach to 'unlocking' channels that have become choked with exotic vegetation. Gravel conveyance may also be improved via regular gravel raking in the river corridor, which may also help manage vegetation growth in the active channel. It should be noted that frequent intervention in gravelly channels reduces channel stability and improves gravel and channel mobility. This means that rivers raked or skimmed to improve gravel conveyance will require more room to accommodate this enhanced activity.

To reduce reliance on rock lining laterally active channels, a more sustainable alternative is to allow the dynamically adjusting river to dynamically adjust: let the river be a river and do what rivers do. Long-term this is likely to be the more financially prudent option, although initial costs will be required if land is to be purchased for retirement from production and return to the river. Allowing the river room to erode will increase the geomorphic and habitat diversity in the river corridor and improves resilience in the face of increased flood magnitudes. Larger floods, occurring more frequently will require more room to be accommodated. It is better to accept this reality than endeavour to keep a river constrained in a corridor which is simply too narrow to contain it. A widened corridor allows for bank erosion and bend migration, and cutoff, and braid development. A widened corridor accommodates larger floods, which can happen without resulting in significant losses to land, infrastructure and even life, or substantial change to the form of the river, which is much better adjusted to accommodate large floods and does not require intervention to 'fix', because the natural processes of erosion and deposition within the river corridor enable the river to fix itself.

A strategic change in the direction of river management - away from a 'command and control' ethos that has dominated practice for over half a century and proving to be unsustainable (particularly in the light of forecast climate change and associated shifts in flood magnitude and frequency), towards a 'living with the river' ethos - is multi-generational in scope, and should be culturally-informed. It is simply unfeasible to walk away from river corridors with the infrastructure and investment and livelihoods that are bound up with the current practice of 'control'. A phased approach is needed and communities will need time to appreciate and understand the changes in practice. Such an approach should form part of a Floodplain Management Plan, which in any given system needs to explicitly map out the transition from 'command and control' to 'living with the river' in a discrete catchment.

A strategic gravel management policy should give effect to Te Mana o te Wai, which is about restoring and preserving the balance between water bodies, the wider environment, and the community. This entails working with tāngata whenua and communities to set out long-term visions in regional policy statements and plans. Floodplain Management Plans developed for each catchment (above) would be an effective means and appropriate context to give effect to Te Mana o te Wai.

It is important to work with the morphology of river channels and appreciate their natural processes of adjustment (e.g. avulsions, cutoffs, bend development, braiding) in order to work with the river, rather than against it. Working with these processes of erosion, transport and deposition means the river is doing much of the work itself, without the need for large-scale intervention. In the short-term allowing this adjustment may result in apparently negative effects, such as a more 'messy' river corridor. However, 'messy' rivers are in fact more diverse and reflect natural functioning in dynamic systems. Working with the river morphology entails informed understanding of channel dynamics and trajectories in any given reach. This level of understanding should be informed by good science and robust collection and analysis of data, assessing morphological development and changes in sediment storage (and gravel flux) in the system as a whole.

Changes in flood magnitude and frequency must be considered. Bigger floods forecast may help resolve the locked river corridor problem, but larger floods will require more room and channel expansion is to be expected and must be anticipated. However, climate change is not just predicting bigger floods, but also more intense droughts. This situation may mean are less predictable river behaviour in the region and management practices may need to adapt accordingly. To manage the trajectories and responses of Southland's rivers requires a strategic investment in appropriate monitoring programmes, so that river behaviour can be properly understood, rivers treated as the dynamic entities they are and lived and worked with, rather than worked and defended against.

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1. Introduction

1.1 Aim

The aim of this document is to outline a series of scientifically-led strategic principles and recommendations that should underpin and inform gravel management in Southland’s rivers. As such, this report does not provide technical information or detailed analysis of data, but presents a high-level, geomorphologically-informed overview in order to inform a future Strategic Gravel Management Policy. Such a Policy will necessarily be informed by a range of contributors, including ecologists, planners and tangata whenua.

1.2 Catchment context

Strategic principles and recommendations for gravel management must be grounded on a thorough understanding of each catchment drained by a specific river. The nature and characteristics of a catchment exert a fundamental control on key boundary flux conditions, which are essentially the flux in water and sediment delivered from a catchment to its river network, moderated or amplified by channel slope. Steeper channel slopes increase stream powers for a given discharge and increase sediment transport capacity for a given sediment volume delivered to a river channel.

Passive catchment controls on runoff (i.e. those controls that are consistent between rain events) include underlying rock type (lithology), drainage density, topography (relief), land-use and land cover in the catchment. These variables also condition the nature (volume and calibre) of sediment delivered to the stream network, moderated or amplified by the linkages or connectivity characteristics in a catchment, i.e. how well connected slopes are with the channel network, and in turn how well connected that network is that feeds the trunk rivers, which are usually the object of gravel management. Figure 1 summarises the range of catchment-specific characteristics and linkages to take into account when assessing boundary flux conditions in any catchment. In addition to listing these characteristics and linkages, there are spatial considerations and disturbance responses to consider, which tend to be site specific (Figure 1).

Any one catchment has a complex assemblage of these components. The characteristics and linkages of a catchment feeding any river essentially generate a unique supply of water and sediment and energy to that channel at that point in space and time. This in turn means that what the river channel looks like and how it behaves and adjusts to fluctuations in these boundary-forming conditions is unique in space and time. Figure 2 stylistically summarises a combination of erosion sources and processes connecting sediment to a channel (catchment conditions), influenced by rainfall and climate regime and land cover (bioclimate conditions) to drive a unique combination of channel forming boundary conditions (discharge, sediment, channel slope).

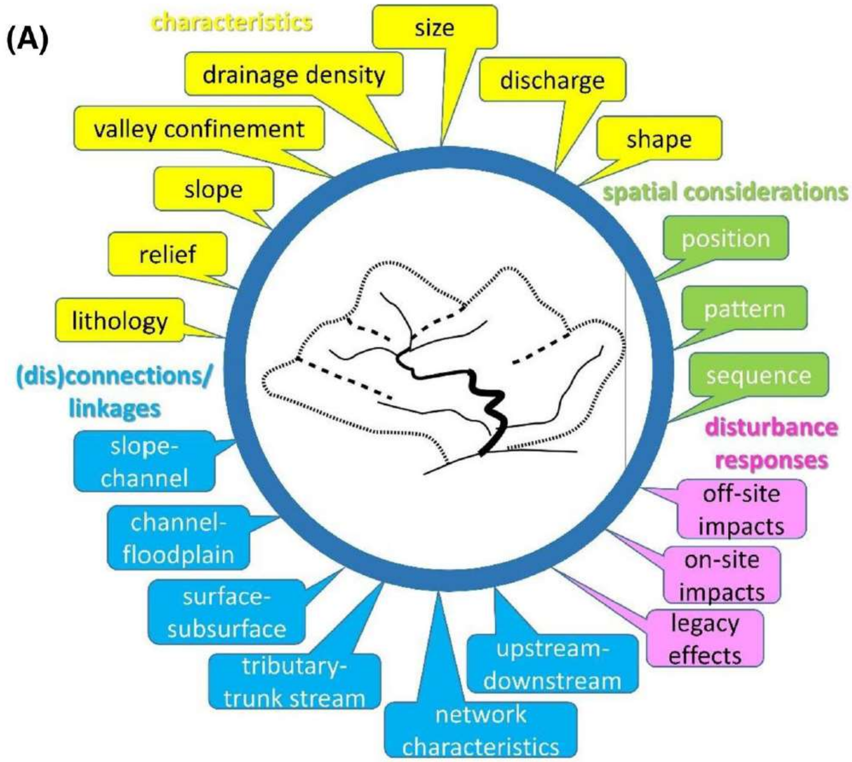

Figure 1. Characteristics, linkages, spatial considerations and disturbance responses of catchments, source: Figure 2A, (Brierley and Fryirs, 2022).

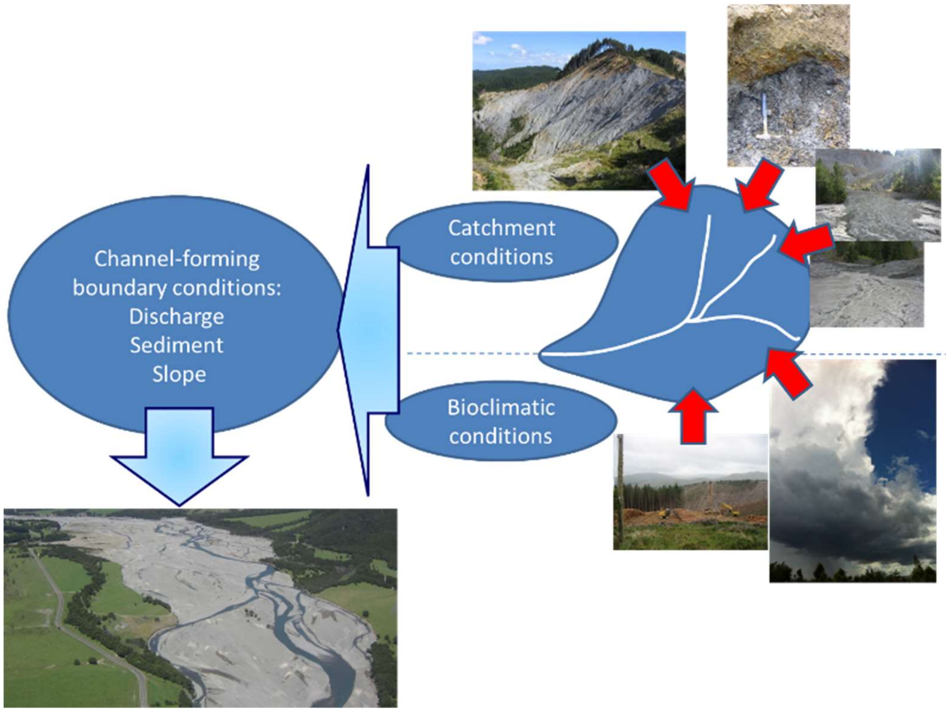

Figure 2. Stylised representation of each river reach as being unique in space and time, since it reflects a unique combination of channel forming boundary conditions (flux conditions) in time and space.

1.2.1 Sediment conveyors

Where a reach of river sits within its catchment must be taken into account when assessing its characteristics, behaviour and likely trajectory to inform gravel management, because rivers act as 'sediment conveyors' in their catchment (Figure 3).

Sediment is sourced from two key areas in any catchment:

i. Original generation from the source, or production zone, i.e. the catchment headwaters and / or adjacent slopes that are coupled with the river channel.
ii. Reworked alluvial deposits that have been originally sourced from the production zone, but temporarily stored in river terrace and floodplain deposits in the transfer zone (Figure 3).

Reworking of gravel stores in floodplain and adjacent terraced alluvium as rivers adjust laterally makes an important contribution to the coarse load of river systems and has even been cited as contributing to planform change along some systems (Schumm, 1985). Conversely, erosion of soft-rock hill country provides an important primary source of fine sediment in many New Zealand catchments. Where a river gets its sediment from within its catchment is critical to understand its form and potential transformation of that form over time.

Disruption of the sediment conveyor (Figure 3) can have significant unintended consequences both upstream and downstream of a disturbance site. Gravel extraction from the catchment accumulation zone (Figure 3) is likely to have fewer consequences than extraction from source or transfer zones (Figure 3) because the river lacks the energy to transport gravel farther downstream, so removing it is likely to result in local site impacts. Taking gravel farther upstream disrupts sediment supply to downstream reaches, potentially starving the river of its bedload, likely resulting in channel erosion both of the bed and undercutting of banks. When assessing river characteristics and behaviour a good rule of thumb is always to consider 'bed before banks' (Brierley, personal communication, 2023) because how the bed behaves will affect bank stability, regardless of how the bank may be 'treated' (e.g. riparian plantings, rip-rap, rock lining, groynes etc).

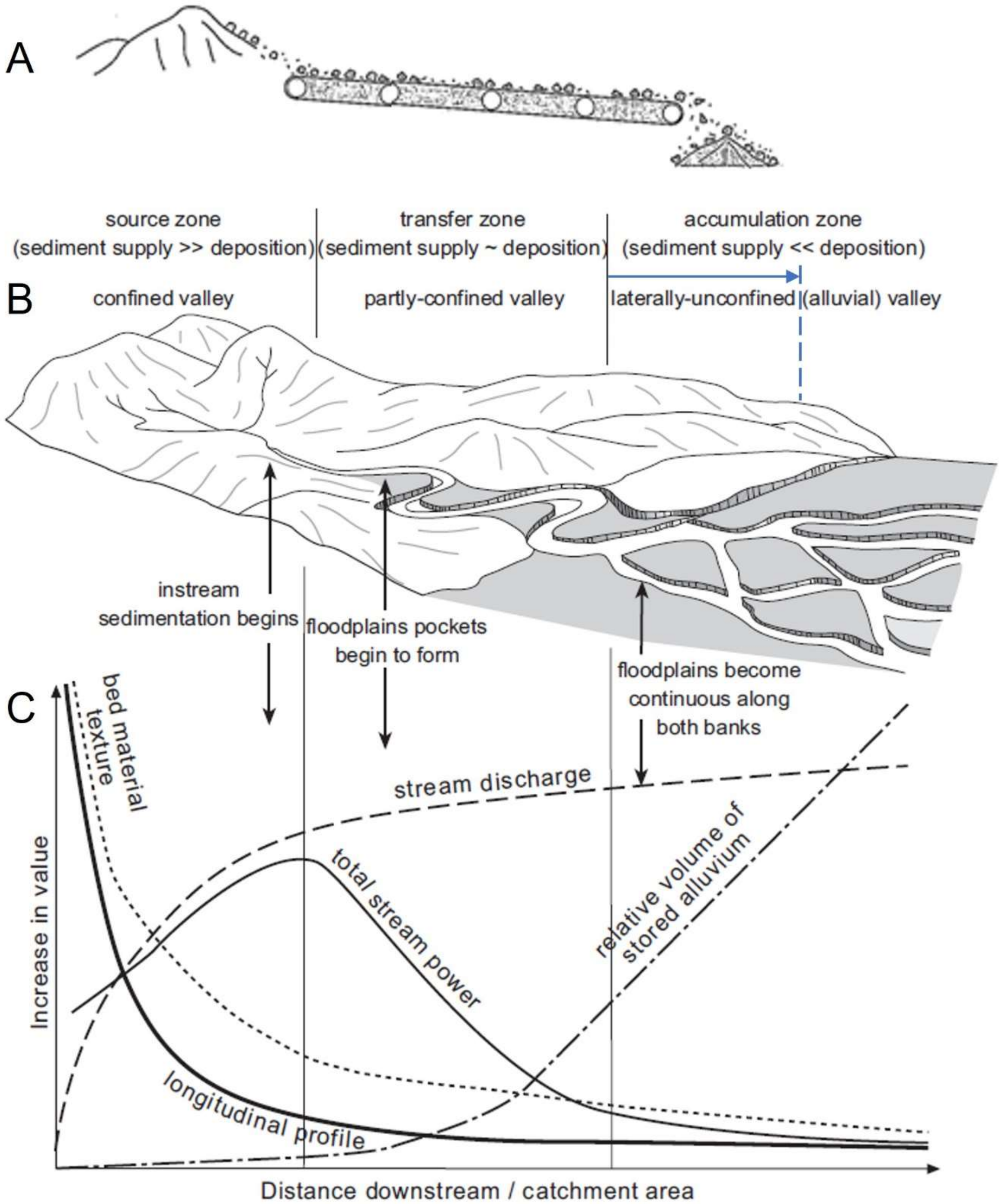

Figure 3. The catchment sediment conveyor (A), conceptualising the relationship between source, transfer and accumulation zones, valley confinement, and in-stream sedimentation and floodplain formation (B), and the river system attributes in relation to drainage area (C). Modified from Fryirs & Brierley, 2013). Note that the transfer zone is not necessarily limited to partly-confined valleys, higher energy (e.g. braided) rivers are competent to transfer material in unconfined settings (blue arrow and line).

The sediment conveyor is not smooth, but jerky, which means sediment is conveyed often as a series of pulses, bedwaves, or slugs (Nicholas et al., 1995). Individual particles are moved in discrete steps, with intervening periods of inactivity. Gravel transport is intermittent and only takes place when flows are sufficiently powerful to mobilise and transport this calibre of sediment. A complex relationship exists between a threshold discharge, or stream power, or shear stress and the point at which gravel-sized material begins to move on a riverbed. The relationship is complex because gravel clasts are generally structured or imbricated or embedded in the riverbed, which becomes ‘armoured’. The more structured the bed of a river, the more energy / power / shear stress is required to mobilise gravel clasts of a given size. Structuring of the bed and development of an armour layer adds stability to the riverbed and increases resistance to transport. Armouring develops in supply-limited rivers, i.e. where sediment supply is limited in relation to flow competence (size of material that can be transported) and transport capacity (the amount of material transported) (Rhoads, 2020). This situation is the case for most Southland rivers, for most of the time, which affects gravel conveyance and contributes to the jerkiness of the conveyor.

Once an armour layer has developed, higher flows are required to break up this armour in order to entrain gravel clasts. During a period of smaller floods and lower-energy flows, riverbeds tend to become increasingly armoured and the bed increasingly stable. During these periods mortaring of clasts may also occur, where fine sediments effectively act as a weak cement between gravel clasts, particularly where fines are draped over an immobile gravel bed. This process tends to occur on bar surfaces within the active channel when flows are sufficient to inundate these areas and deposit fines, but lack energy to entrain the gravel. Following a sustained period of lower flows / smaller floods, a much larger flood is required to re-mobilise well-armoured, mortared gravels in the active channel, especially from higher bar surfaces in the active channel. Conversely, a succession of larger, bed-disturbing floods prevents gravel surfaces from becoming over-armoured and locked. Nevertheless, gravel transport will only occur during flow events of sufficient magnitude to mobilise gravel of a given size in any reach of the catchment.

Travel distances of gravel (step lengths) are dependent on particle size (larger clasts have smaller steps). The path length is the total amount of displacement of a gravel clast during a particular flood event and this consists of multiple steps. The path length also declines with increasing particle size. Path lengths of all particles increase with excess stream power (stream power that exceeds entrainment thresholds). How far gravel moves during an event therefore depends on the magnitude and duration of a given event, as well as particle sizes mobilised.

The nature of the transfer zone is that the river has sufficient energy (slope and discharge) to convey sediment through these reaches on the whole. However gravel transport is not continuous, but intermittent, which means that river reaches that are by-and-large transporting gravel through them will nevertheless experience alternation between aggradation and degradation in time. Since there is variability in gravel conveyance over time, there will also be variability spatially between reaches, with adjacent reaches behaving differently. As pulses of gravel move through the system they are linked with increasing channel activity. Increased activity may be reflected in local channel expansion, increased braiding intensity, bend migration, chute channel cutoff or avulsion. Spatially, an ‘hour-glass’ alternation may be apparent between wider, more active reaches and narrower less laterally active reaches. In rivers where the channel has the capacity to adjust (i.e. it is not confined e.g. by valley sides, terraces, or artificial constraints), more laterally active reaches may become partially or fully braided, relative to more single-threaded wandering, or meandering reaches.

The spatial and temporal variability in gravel conveyance depends upon the jerkiness of the conveyor, reflecting sediment flux and supply both from upstream and lateral reworking of alluvial deposits, as well as the variability in flow (energy to mobilise the material). Since most gravel on a riverbed will move only during flood flows, which exceed sediment transport thresholds, flood-rich phases (i.e. periods of time characterised by higher frequency of above-threshold flows) will increase gravel conveyance and, accordingly, potentially increase channel activity. Conversely, flood-poor phases (i.e. periods of time characterised by fewer and smaller floods) will likely reduce gravel conveyance and may lead to ‘locking up’ of gravel stored in the active channel corridor, particularly when gravel beds become strongly armoured and mortared, as described above.

In the depositional zone in a catchment, at the ‘end’ of the sediment conveyor (Figure 3), stream energy drops below gravel transport thresholds and the river lacks the power to transport the coarsest fraction of its bedload (gravel) due largely to channel gradient change. Flattening of the channel slope reduces stream energy and gravel is deposited. This point in the catchment sediment cascade is also described as the gravel-sand transition, because downstream from this point, the river is only competent to transport sand size material (Figure 3). Gravel may therefore be naturally absent in the lower courses of otherwise gravelly rivers: the Manawatu River, for example, lacks the energy to transport gravel to the coast and deposits its gravel load at Opiki (Page and Heerdegen, 1985).

1.2.2 Channel forms and sediment

The availability of sediment, its supply and transportability in a river in turn shapes the channel form (Figure 4). A range of river types may therefore be expected in gravel-bed rivers. Gravel-bed rivers are characterised by high width:depth ratios (i.e. wide and shallow), in contrast with suspended load dominated systems, where finer grained, cohesive sediments lining the channel limit lateral adjustment and generate typically low width:depth ratio channels (i.e. narrow and deep). Changing catchment sediment supply can result in transformation of river channel form since the form of the river is largely dependent on the sediments lining the channel. Increased supply of coarse, bedload calibre material will promote conditions favouring wide, shallow, gravelly channels, whilst over-supply of fine suspended can result in channel narrowing. Channel contraction and bed incision in gravelly rivers also occurs in response to reduction in gravel supply and conveyance, both at a reach scale, as discussed above, as well as a catchment scale.

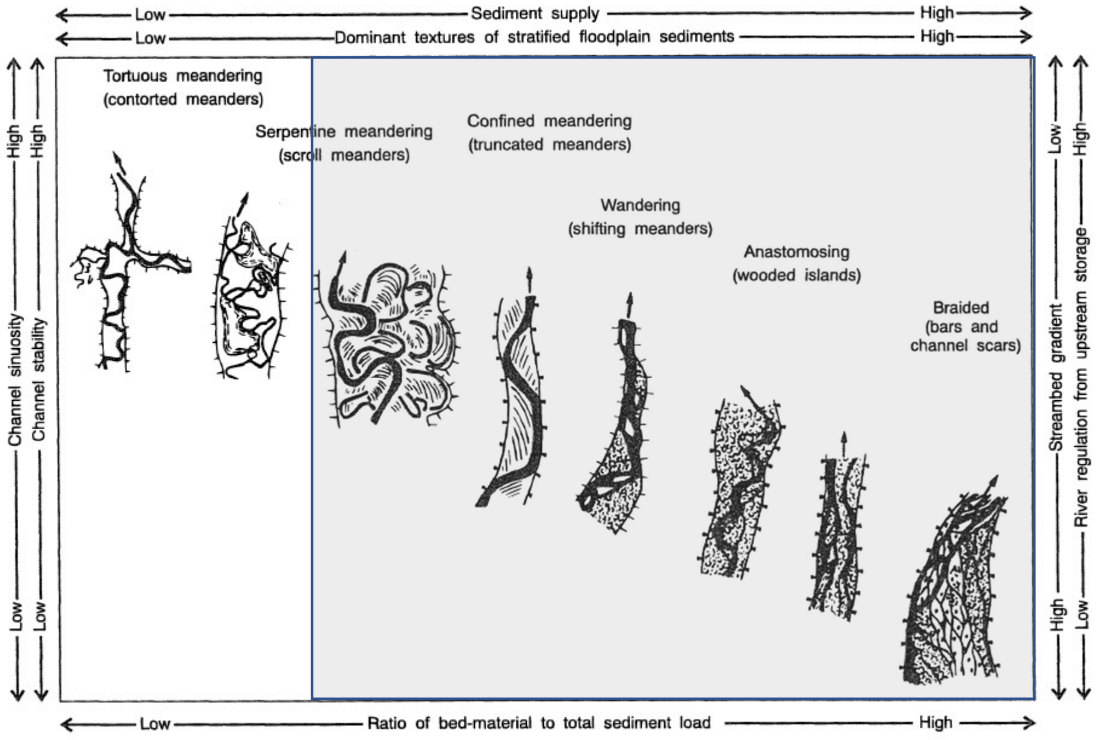

Figure 4. Continuum of river channel types and controlling variables, highlighting the spectrum of gravel-bed river types (shaded), after Mosley (1992). Note: sediment supply is predicated on coarse (bed calibre) material in this diagram.

Where Southland’s principal rivers are unconfined by valley margins or river terraces, their natural form ranges from braided, to wandering, to meandering, which reflects contrasting boundary flux conditions between catchments, as well as changes in energy conditions along a river. For example, the Oreti is braided or semi braided (wandering) for most of its unconfined length between Mossburn and Winton, but transitions to a more single-threaded, meandering form downstream from Winton. This change in river form reflects a reduction in the energy in the system to convey sufficient bedload end effect sufficient channel widening to allow braiding. The form of the contemporary river channel differs from previous channel traces observed in the adjacent floodplain in the vicinity of Winton (Figure 5). Figure 5 shows a wandering channel today where palaeochannels on the adjacent floodplain appear to show a distinctly meandering pattern, as do aerial photos from 1939. However, careful scrutiny of the former channel courses in the LiDAR image shows that at some stage prior to the meandering here, there is evidence for a more braided pattern at this location. This illustrates the propensity for these gravelly rivers to change both in space and over time as boundary flux conditions change. Straightening of the Oreti in this reach would have increased stream energy, extending the more dynamic wandering / semi-braided pattern farther downstream.

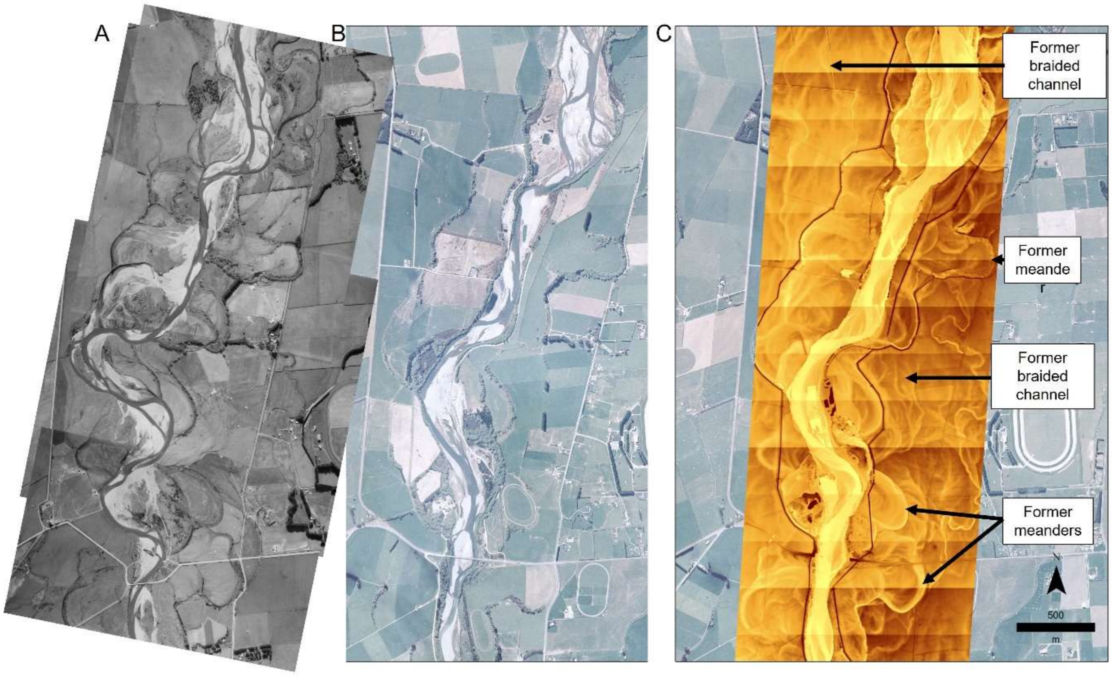

Figure 5. Oreti River near Winton, A: 1939, B: 2005, C: 2020 LiDAR, highlighting historic, recent, and present channel morphologies. Note that the LiDAR image reveals the presence of former channels within the currently active channel, which are not presently occupied by water, but serve as ‘flood gutters’ and may activate during high flows and into which the current wetted channel may avulse (switch).

2. Data requirements for effective gravel management

A quantified gravel budget is needed to understand whether gravel extraction is appropriate, sustainable, or likely to result in damage to the river corridor (see Appendix 2).Large aggrading gravel-bed rivers in New Zealand could be considered relatively resilient to gravel extraction when compared with small single thread rivers (Holmes, 2017). However, as Holmes (2017) goes on to report, there remain significant effects of gravel extraction, even on large braided rivers. The effects of gravel extraction are important to consider in forming a gravel management strategy, but are not the intended focus of this report. A review of gravel extraction effects was undertaken by Fuller & Death (2021) and this review is included in Appendix 2. Extensive, braided reaches in Southland's rivers should not be considered as being able to sustain unlimited, or uncontrolled extraction, despite the *appearance* of an abundance of gravel.

Critical to gravel management in Southland rivers is understanding the flux of gravel in these systems. The delivery of gravel to the channel varies over time and the conveyance of gravel along the active channel will fluctuate as flood magnitudes and frequencies fluctuate and gravel is pulsed through the system in a series of bed waves / gravel slugs / gravel sheets. An effective gravel management strategy must, therefore, be predicated on reliable information on the gravel load of Southland's rivers. Understanding gravel transport processes and supply rates is critical and fundamental to inform gravel management. A quantified gravel budget can be achieved in several ways, but the emphasis is on having longitudinal data in order to monitor how gravel is moving through the river system. The following section discusses two different approaches to gravel budgets - channel cross-sections and channel DEMs.

2.1 Approaches to quantifying gravel budgets

There is (still) very limited information on gravel supply rates in New Zealand rivers (Kelly et al., 2005). However, Williams (2011) does present estimates of gravel transport rates in selected rivers using a combination of a volume-balance approach derived from repeat cross-section surveys and a sediment rating approach using sediment transport formulae. The problem with using sediment transport formulae, however, is the use of a uniform grain size, usually median (D_{50}), with no accounting for bed structure or sediment heterogeneity and the assumptions of uniform flow and roughness, which do not reflect the reality in gravel-bed rivers; accordingly Williams (2011) found up to a full order of magnitude difference between three different bedload formulae applied to the same dataset and substantial differences between transport rates derived from formulae with those derived using a volume-balance approach. Sediment transport formulae are no substitute for field-based measurements when attempting to understand gravel flux.

Measurement of bedload transport in gravelly rivers is nevertheless notoriously difficult, and direct measurement using bedload traps and tracers is not likely to be feasible. However, since the shape and form of a gravel bed river reflects the way gravel bed has been moulded in response to gravel movement and deposition in the channel, assessing changes in channel morphology can be used to provide a realistic assessment of gravel storage and changes therein using morphological budgeting (Fuller and Basher, 2013). Morphological methods to estimate gravel flux have been used in New Zealand, based on channel cross-section surveys (Griffiths, 1979; Noell and Williman, 1992; Sriboonlue and Basher, 2003; Williams, 2011; Williams et al., 2014), as well as DEMs (Lane et al., 2003; Fuller and Hutchinson, 2007; Hicks, 2012; Fuller and Basher, 2013; Neverman et al., 2016), which can also be linked to modelling (Larned et al., 2008; Javernick et al., 2016). Morphological budgeting, particularly using Digital Elevation Models (DEMs), has the advantage of also providing information on river channel morphology and change in form along the river corridor and over time. As such, not only are changes in gravel storage being assessed, but the impacts on river morphology and identification of hotspots of erosion (lateral, or bed degradation) and / or deposition (bed aggradation) in connection with channel adjustments can be realised.

2.1.1 Channel cross-sections

In addressing gravel management, a key question to consider is posed by Tunnicliffe and Baucke (2021:41), "how much gravel can be sustainably removed from a river reach as a proportion of the annual resupply rates?", which is referred to as the bed material extraction ratio. Tunnicliffe and Baucke (2021) note that most management approaches in NZ involve post hoc assessment of mean bed levels relative to a established grade line[1] (Basher, 2006; Ecan 2006; Clode and Beya, 2018). In theory gravel extraction is considered sustainable as long as the river does not degrade below this pre-determined grade line, but this does not take into account variability in sediment flux or the natural dynamism and sensitivity of the system. Furthermore, as Clode and Beya (2018) comment, the calculation of a grade line is qualitative since a filtering process is used to produce a smooth line, which ignores natural topographic highs (riffles) and lows (pools). Tunnicliffe and Baucke (2021) use the concept of a grade line as the Mean Bed Level (MBL, which is the integrated average of vertical change at all points across the active channel at a given cross section) first measured at a cross-section, with subsequent departures in stored volume from this point in time reflecting relative change to the system (Tunnicliffe and Baucke, 2021, Figure 6).

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[1] "A grade line is a concept for managing gravel extraction by providing a 'benchmark' at a given location by which the variation of sediment storage is measured and described as a surplus (positive) representing an increase in bed level or a deficit (negative) representing a decrease in bed level. Grade lines are based on design mean bed levels for which the mean annual flood (which is exceeded one every 2.3 years on average) just fits within the active channel before overflowing onto the berms (floodplain). This definition is supported by the understanding that the average yearly flood, typically estimated by the design 2.3 year return period peak flow, is the main channel forming event for mobile-bed rivers. Typically this definition applies to the managed channels within the flood protection schemes managed by HBRC. In a less controlled situation where the valley gradient can change and the river is free to adjust its channel to accommodate the change in energy gradient, a single gradient grade line may not be a sufficient benchmark requiring multiple gradients over a reach in order to best use this concept." Clode & Beya (2018, p.14).

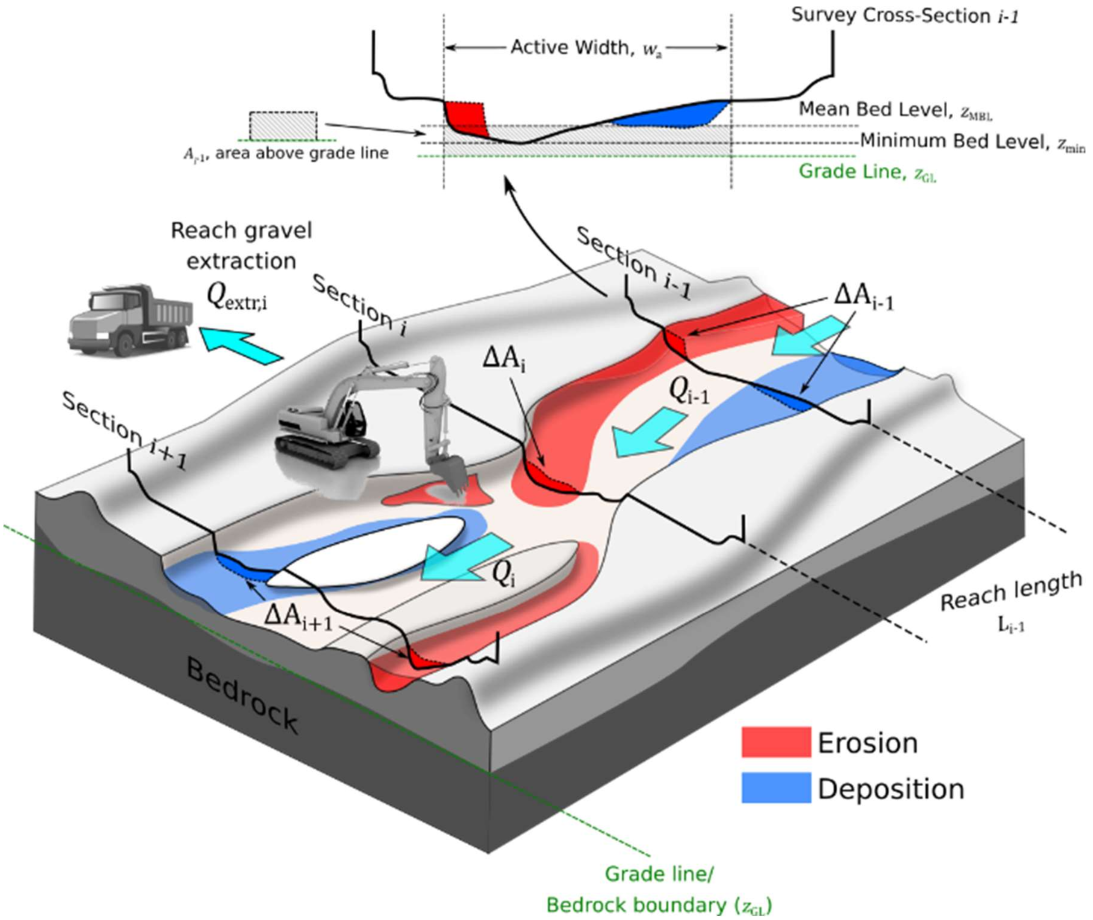

Figure 6. Schematic diagram illustrating morphological changes associated with gains (deposition) and losses (erosion) of gravel as may be assessed using cross-sections. Spacing of reaches (reach length between adjacent cross-sections) should approximate the transport length[2] of gravel in the system. Gains and losses measured along a cross-section are assessed, with the balance routed downstream as sediment discharge (Q). If this balance remains close to zero the system is in equilibrium in terms of gravel storage, where it is positive (i.e. more gains than losses) it aggrades and conversely where negative it degrades (from Tunnicliffe and Baucke, Fig 3.32).

Changes in channel cross sections, reported as rise or fall in mean bed level (MBL, cf. Figure 6), can reflect the magnitude of changes in gravel storage in a reach. However survey of cross-sections is generally on an approximately 5 yearly basis. In the Oreti River, cross sections in the reach between Winton and Branxholme were surveyed in 2009, 2013 and 2020. Analysis of these surveys can be helpful to display overall trends between successive surveys (Figure 7). However, between successive surveys, considerable scour and fill can occur during intervening gravel-mobilising flows. In addition, changes between cross sections are not accounted for and significant changes in sediment storage are

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[2] Transport, or path length is the mean travel distance of gravel clasts over time, e.g. during a flood event (Vericat et al., 2017). There is considerable variability in the relationship between path-lengths and channel morphology (Pyrce & Ashmore, 2003). At higher flows travel distances may be related to specific morphological units (e.g. bar-pool spacing) and flume studies have shown that path lengths relate to bar spacing and bar heads were consistent sinks for tracers used in analysis (Kasprak et al., 2015), eroded from upstream adjacent scour hole. Effectively, on average the transport path length of a given particle is thought to approximate one half of a meander wavelength, i.e. from erosion at a scour hole, or outside bend to deposition at the next bar downstream (Tunnicliffe and Baucke, 2021).

not included using cross-section analysis (Fuller et al., 2003). Furthermore, if cross-section spacing is not adjusted to accommodate transport lengths of gravel in a system, meaningful estimation of gravel flux becomes problematic: assessment of gravel transport rates requires explicit consideration of transport path length (Tunnicliffe and Baucke, 2021). Further details on the use of channel cross-sections to derive gravel flux are provided by Tunnicliffe and Baucke (2021).

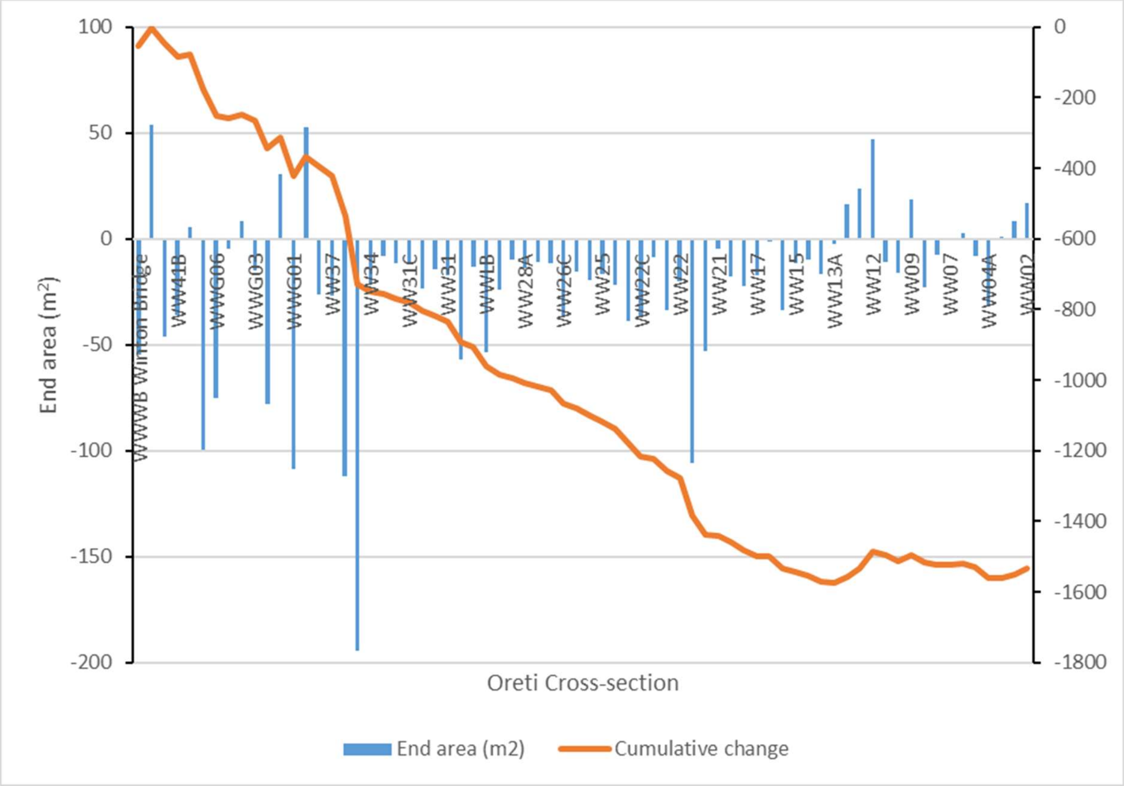

Figure 7. Oreti changes in end area for cross sections between Winton and Branxholme between 2013 and 2020. The immediate trend indicates bed lowering, indicative of sediment starvation. However, this overall trend masks significant compensating erosion and deposition between surveys. Nevertheless, a degradational trend is striking on the basis of these data. Note, flattening of the cumulative curve from WW13A suggests this section of the river is a natural accumulation zone where gravel is deposited in response to loss of stream competence to transport it farther downstream (cf. Figure 3).

2.1.2 Channel DEMs

A more holistic approach to quantifying gravel budgets is provided using survey approaches that generate topographic data from the active river channel to generate a continuous surface visualised as a Digital Elevation Model (DEM). Differencing a surface (DEM) from one time to another generates a DEM of difference (DoD), from which volumetric change over time is determined. Topographic data have been generated in New Zealand river environments to generate DEMs at a reach-scale using ground survey (e.g. Fuller and Basher, 2013; Neverman et al., 2016), terrestrial laser scanning and optical bathymetry (Williams et al., 2014), and Structure from Motion photogrammetry (Tunnicliffe et al., 2018). A recent example from the Waiapu catchment reveals the level of detail and information on volumetric change that can be generated using DoD approaches (Figure 8). While the spatial extent of these studies has been limited to date, recent acquisition of LiDAR now makes whole-river corridor topographic survey feasible (e.g. Fuller and Conley, 2023).

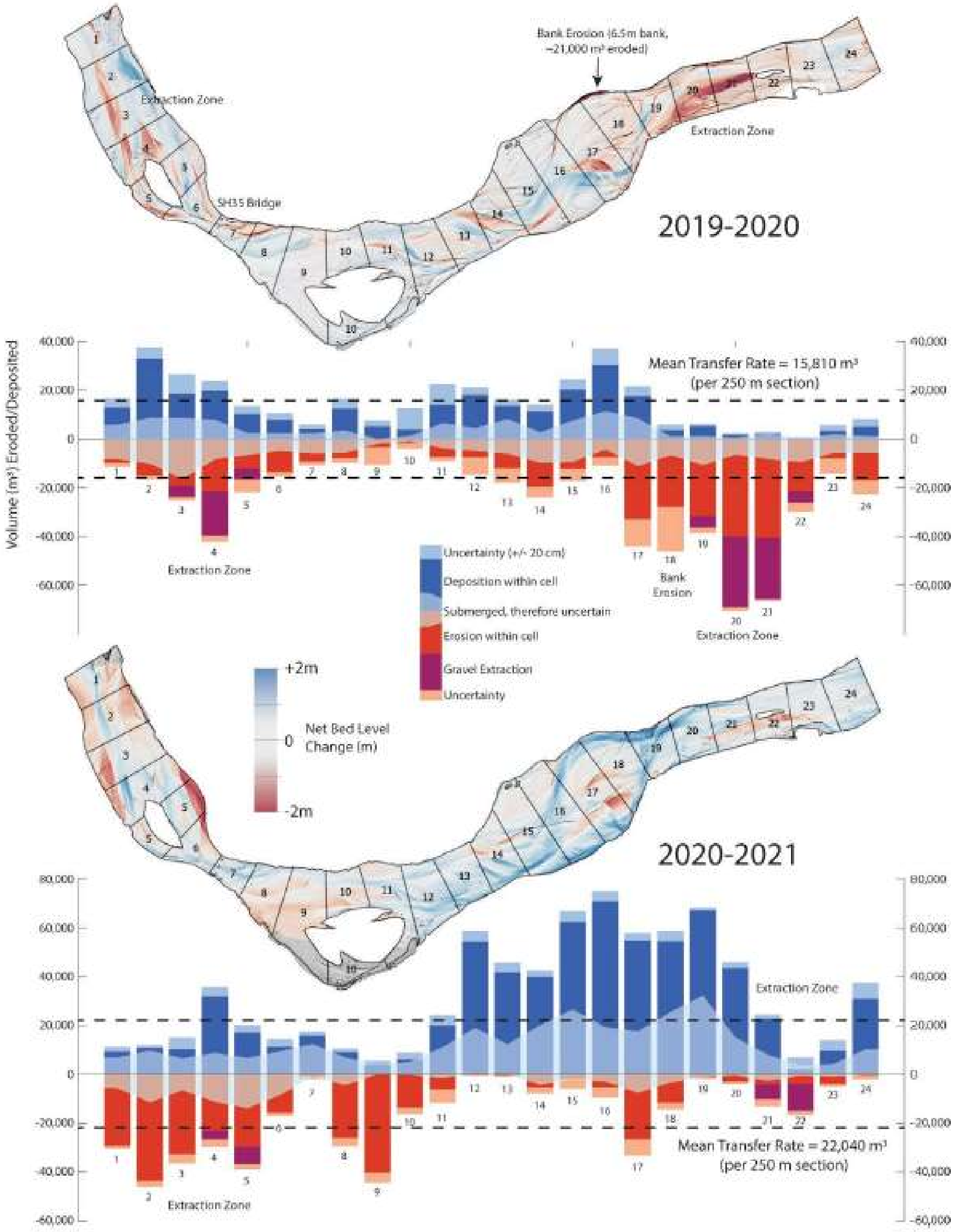

Figure 8. DEM of difference (DoD) for the Waiapu River presented in Tunnicliffe and Baucke (2021, p. 46), showing gains (blue) and losses (red) along the active river channel for 6 km downstream from the Tapuaeroa-Mata confluence. Bars show quantum of sediment eroded and deposited in each segment.

The advantages of DoDs over channel cross-sections in informing gravel management are clear. Gravel fluxes and changes in gravel storage can be quantified with an improved level of confidence and accuracy and linked to channel morphological changes, including quantification of inputs from bank erosion, storage in abandoned channels, erosion from avulsing channels. A much more rigorous assessment of river behaviour and morphological change is captured by successive DEM differencing using LiDAR flown along river corridors when compared with cross-section data. Topographic data captured using LiDAR are acquired in a short window, i.e. the time it takes to fly the corridor (usually within 1-3 days, depending on river length). In contrast, a survey campaign to re-survey a sequence of channel cross sections may take several weeks, during which a range of flows and potentially multiple mobilising flood events is likely to occur (Fuller & Conley, 2023b). It should be remembered that conventional (red-light) LiDAR does not reliably or consistently penetrate the water column. To ensure consistency in analysis the wetted portions of an active channel should be either excluded or replaced using an alternative assessment of bathymetry if available. However, bathymetric (green-light) LiDAR is now available in New Zealand and should be specified when flying river corridors for the purpose of informing gravel management to ensure accurate and consistent measurement of the entire riverbed. Green LiDAR returns the best results during low flows with low suspended sediment concentration. As such, if acquiring to detect change following a flood event, it is better to wait until river levels have dropped and fines have been flushed.

3. Gravel management options

This section of the report is informed by discussion with Environment Southland (ES) Staff on 14 June 2023. A key problem identified by staff is the increasing vegetation colonising active channels of hitherto bare gravelly surfaces. This section explores two gravel management options – bar top (beach) skimming and alternatives to gravel extraction. It also highlights the need to develop a framework for practice, to allow room for the river to move, and the importance of stakeholder engagement. Environment Southland needs to proactively support the community to understand the need for changes in how the Council manages rivers and the paradigm shift required in order to work in new ways (from 'command and control' to 'living with rivers').

The reason for increasing vegetation colonisation in active river channels likely arises from a period of smaller floods, which drape fine sediment across bar surfaces without mobilising gravels. This has the effect of both increasing embeddedness of the gravels in these surfaces (cf 1.2.1) and providing substrate more suited for vegetation to colonise. The overall effect is to reduce mobility of sediment stored in these vegetated / vegetating bars. Furthermore, once colonised by vegetation, root mats and stems further increase resistance to flows, limiting gravel mobilisation to events that are sufficiently competent to strip vegetation and fine overburden, which tend to be limited to large flood events (magnitude and / or duration). Meanwhile, unable to entrain and replenish sediment from bars within the active channel, the river may respond by incising its bed and / or undercutting banks. Precisely how channels respond to vegetation lock-up is yet to be fully quantified in Southland, this behaviour is drawn from observations made by ES staff, but appears to be intuitive and is consistent with observations elsewhere, which highlight channel narrowing in response to vegetation colonisation of the river corridor (e.g. (Gurnell, 2014).

Much of the vegetation in Southland's river corridors has been classed as invasive exotic species, including (but not limited to) rank grass, lupin, broom, gorse, tree lucerne, and willow. Although willow planting has been deliberate in past attempts to stabilise riverbanks prone to erosion, stems naturally broken from these trees readily colonise bar surfaces within the active channel. It is likely that the composition of Southland's river corridors has changed over the past 100 years with the spread and establishment of exotic vegetation in active channels. This vegetation is also characterised by rapid growth, being early pioneer species, which means if the active channel is not turned-over by flood events every year or two, the corridor can become choked with this vegetation, in turn locking-up gravels until a much larger flood re-sets the active channel by stripping the vegetation and mobilising the underlying sediment (including gravel).

3.1 Bar top (beach) skimming

To address the problem posed by invasive vegetation, ES is undertaking trials of bar-top (beach) skimming to remove the invasive vegetation and fine sediment overburden, to allow the river to re-access gravels stored within the active channel in these bar complexes. Removal of the vegetation and overburden is mechanical. In principle this approach should result in reactivation of these surfaces in the active channel, on the assumption that floods are of sufficient magnitude to (a) inundate the exposed material and (b) mobilise the gravels exposed. There is a risk, especially in a flood-poor period, that flows across these exposed surfaces are not competent to entrain gravel and re-deposit fine sediments that become colonised by vegetation again. There is also the question of whether this approach is actually sympathetic to the natural character of a given reach. Activating a river corridor in this way should be targeted at reaches that would naturally be characterised by adjacent (and or multiple) bare gravel barforms. If a reach is historically stable, e.g. passive meandering, removal of vegetation and overburden from the river corridor is not in keeping with the natural form of that reach. Some investigation of prior river conditions, such as an NCI analysis, would provide some confidence that bar top (beach) skimming would be returning the river towards a more natural condition.

Reaches where bar top (beach) skimming is explored should be monitored to assess the effectiveness of the approach. Monitoring should acquire high resolution topographic data sufficient to build DEMs at repeated intervals, from which DoDs can be derived to generate an holistic understanding of the adjustment of these reaches to (a) initial skimming and (b) response to subsequent flood events. Trials are currently underway at Wrey's Bush in the Aparima and McGregor's in the Whitestone.

3.1.1 Aparima

The Aparima has been the subject of a DoC-managed approach with a view to improving river habitat for black-backed gulls that nest on exposed gravel in the active river channel. At the Wrey's Bush site, the Aparima has historically been a braided to semi-braided channel, but vegetation growth in the active channel reduced gravel mobility and available habitat (Figures 9 & 10). Skimming of vegetation and fine sediment accumulation from the surface of bars in the reach appears to have increased braiding and restored habitat for nesting birds (Figure 11). Whether this approach succeeds in improving gravel mobility and transport should be investigated using repeat topographic surveys of the site to generate DEMs and DoDs.

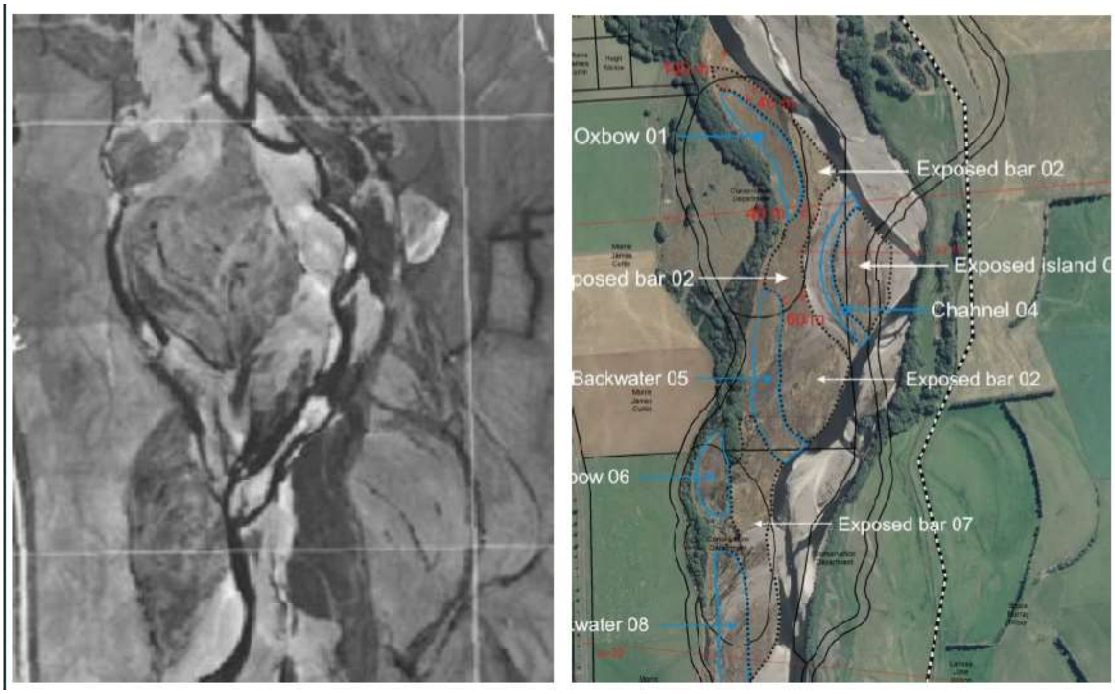

Figure 9. Aparima River at Wrey's Bush, 1950 (left), 2015 (right), source: Figure 7, Hudson (2015) Aparima River Wreys Bush Gravel Extraction Assessment of Environmental Effects.

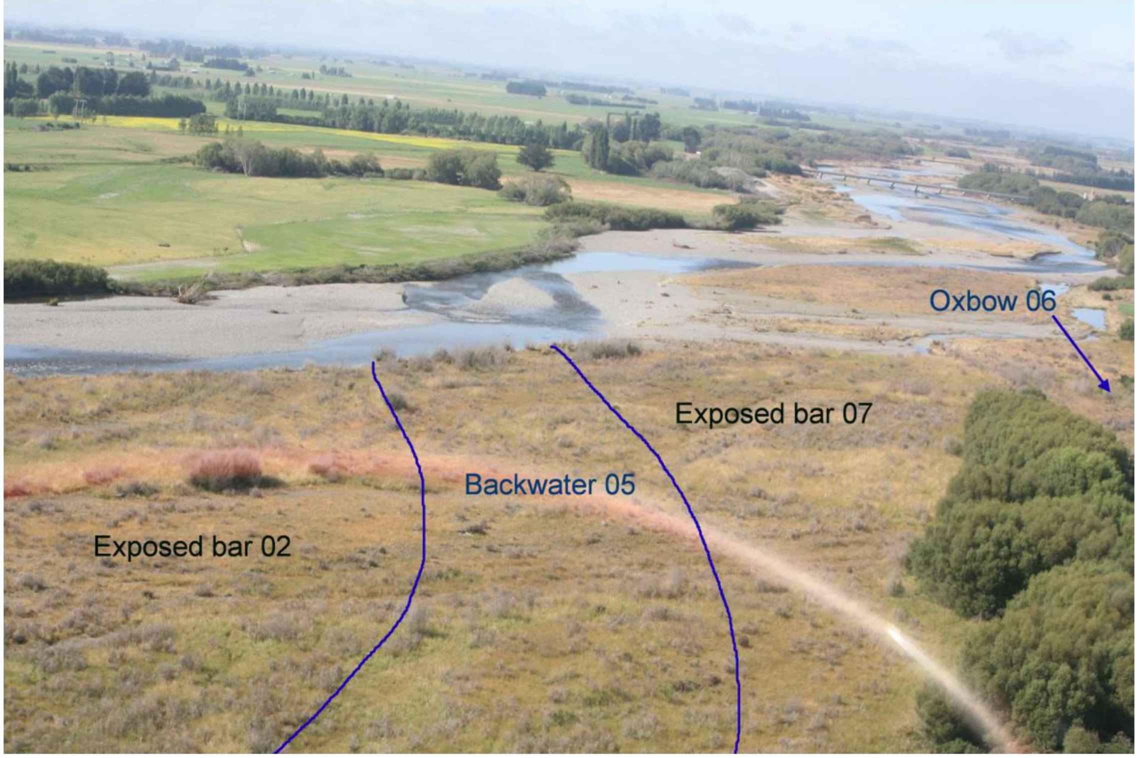

Figure 10. Aparima River looking downstream in 2013, for annotations refer to Figure 9. Note the narrowed largely single-thread channel adjacent to a large area of thickly vegetated bar within the active channel. Source: Figure 8, Hudson (2015) Aparima River Wreys Bush Gravel Extraction Assessment of Environmental Effects.

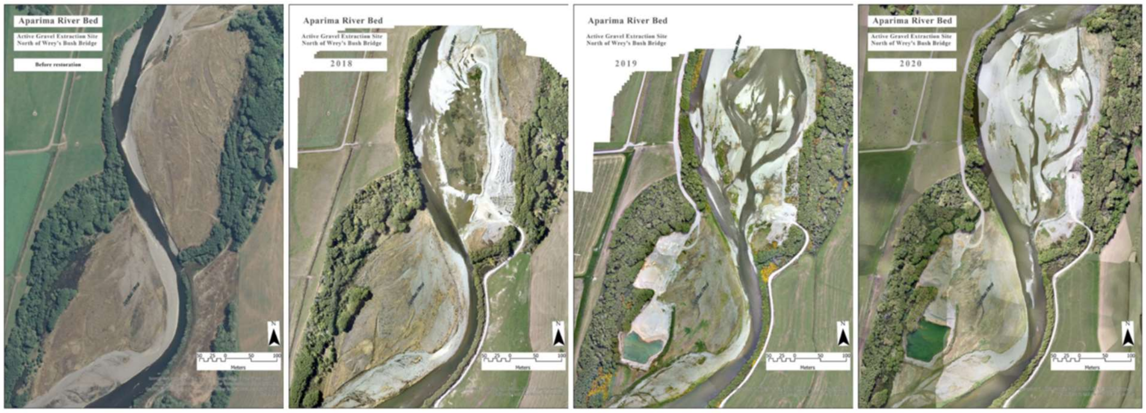

Figure 11. Sequence of aerial images showing Aparima reach at Wrey's Bush pre-treatment (left), mid-treatment in 2018 and post-treatment in 2019 and 2020. Note: flow is from north to south. Removal of the thick sward of grass and soil developed in the active channel has returned the channel to a form resembling its condition in the 1950s (cf. Figure 9). This also displays a contrast between traditional approaches to gravel extraction, which stay away from the water, restrict surface disturbance, dig deep holes, which leave ponds, visible in the adjacent downstream bar. Source: Lagrue & McGregor Aparima River Restoration Project, DoC presentation, 8 June 2021.

3.1.2 Whitestone

A trial like Wrey's Bush was initiated on the Whitestone River in 2021. The Whitestone River at this site (~1 km downstream of SH94) is naturally less braided in character than the Aparima, but the river channel had become particularly narrow and unable to rework its active channel due to thick vegetation cover (Figure 12). Again, whether this approach succeeds in improving gravel mobility and transport should be investigated using repeat topographic surveys of the site to generate DEMs and DoDs. It is notable that the river corridor remains narrower than in 1949, now confined by a road to the east.

Figure 12. Whitestone River at McGregors, 1949 (original, natural condition), 2021 (pre-skimming), 2022 (post skimming). Source: Retrolens and ES. Flow is from north to south, scale approximate.

3.2 Gravel extraction - alternatives

Over-extraction of gravel in Southland's rivers is leading to incision of channel beds. This process has been observed in the Oreti River (cf. Figure 7). The extent of the problem, both within discrete rivers and between different catchments in the region is in urgent need of quantification using 'whole-of-river' morphological budgeting derived from quantifying differences in elevation between Digital Elevation Models (DEMs) as outlined in Section 2.1.2. Incising areas need to be identified because gravel extraction is not the option if the river is in gravel deficit: the problem of incision will be worsened. However, gravel extraction has often been used as the tool of preference to manage apparent gravel build-up in river corridors. Gravel build-up may be temporary and localised, reflecting gravel conveyance along a river as a series of gravel sheets / slugs / pulses (Section 1.2.1), rather than reflecting long-term bed aggradation in a system. Morphological budgets will enlighten the spatial and temporal patterns and processes involved in gravel conveyance along Southland's rivers and help understand the dynamics and trajectories of given reaches. Gravel extraction is not necessarily required to deal with localised build-up of gravel, the key is facilitating mobility of that material to improve conveyance along the channel.

Gravel conveyance may be improved by gravel raking of exposed bar surfaces in the active channel (which assumes vegetation cover is either minimal, or has been removed, or may be intended to be removed as part of this treatment). Gravel raking has been deployed by Hawkes Bay Regional Council in key rivers since 2003 (Clode and Beya, 2018). Raking rips the upper layer of gravel bars (beaches) to break natural armouring (cf. section 1.2.1) as well as uproot vegetation to increase gravel movement and maintain braided morphologies (Clode and Beya, 2018). As such it might be argued that there are three primary objectives to raking bar surfaces in river corridors:

1. Improve gravel transport
2. Manage vegetation build-up
3. Maintain channel morphology

Raking involves dragging a tractor-mounted ripper across exposed gravel bars during low flows in summer the after nesting season and when river levels are low to cover more area (Clode and Beya, 2018). Care is taken to avoid ploughing underwater and avoid increasing the suspended sediment concentration in the rivers. The raking operation is controlled through two key documents: *The Environmental Code of Practice for River Control and Waterway Works*, Clode and Groves, Feb. 2017 and the *Ecological Management and Enhancement Plans*, Forbes Ecology.

The effectiveness of gravel raking in Hawkes Bay rivers has been assessed using a modelling approach by Measures (2012). Results from that study indicated that including gravel raking in the model was found to significantly reduce surface grain size and increase transport rates, suggesting that raking has significant impacts on gravel transport. Raking encourages gravel transport by: (1) mixing the surface layer with underlying material, which influences the surface composition by increasing the proportion of fine grains on the surface, which reduces armouring; (2) loosening the grains so there is less interlocking/imbrication, allowing gravel transport to occur at lower thresholds (cf. section 1.2.1) (Measures, 2012). The extent to which gravel transport was increased by raking in modelled results was dependent on the extent of mixing at the bed surface. Where fully mixed, transport rates of up to 100% were modelled (Measures, 2012). In this modelling approach, raking was shown to produce degradation (or reduced aggradation) of raked reaches and increased deposition downstream (Measures, 2012). In sum, raking of gravel bars in gravelly rivers may increase gravel conveyance. Further work is needed to assess ongoing effectiveness of raking using high resolution field data (as may be obtained using LiDAR or Structure from Motion photogrammetry [SfM]). In particular the longevity of impacts of raking is unknown because once mobilising (above transport thresholds) flow has occurred, the bar surface is likely to become newly armoured, so the effectiveness may only be good for the first mobilising flood. Nevertheless, HBRC appear to have found this approach to be effective in maintaining their active river channels and keeping them free from vegetation. However, mechanical intervention is required annually at end of summer for this treatment to be effective, less frequent treatment allows invasive vegetation to become established and smaller floods (freshes) will develop armour and tend to lock up the material again. Furthermore, raking likely works best in finer gravel, not boulders / cobbles, which are simply not moved sufficient distances, except during a sustained period of high flow (long-duration flood, or high magnitude event). Flood magnitude and frequency likely contributes to the degree of success in raking, but that needs to be established by investigation.

Finally, it should be noted that frequent intervention in gravelly channels reduces channel stability and improves gravel and channel mobility, as has been demonstrated on the Waingawa River in the Wairarapa (Fuller and Conley 2024). This means that rivers raked to improve gravel conveyance will require more room to accommodate this enhanced activity and it will be important to work with these processes and channel morphologies.

3.2.1 Working with channel morphologies

It is important to work with the morphology of river channels and appreciate their natural processes of adjustment (e.g. avulsions, cutoffs, bend development, braiding) in order to work with the river, rather than against it. Working with these processes of erosion, transport and deposition means the river is doing much of the work itself, without the need for large-scale intervention. Within the active channel of muti-thread channels (braided and semi-braided or wandering), former channel courses of the main thalweg are usually present (cf. Figure 5). These recent former channels or 'flood gutters' within the active channel corridor could be opened up to improve conveyance of water and sediment through the system and reduce pressure on the outside of bends where room to move is not feasible. Re-activating these features in the active channel generally requires small-scale intervention at the head of these channels and avoids the need for large-scale excavations in the river corridor. Furthermore, in time these former channel courses would reactivate in any case as during high flows water will take the shortest path. Bends that develop will in time cutoff. Understanding these dynamics can avoid significant rock lining of bends that will become redundant in time. Working with the river morphology entails informed understanding of channel dynamics and trajectories in any given reach. This level of understanding should be informed by good science and robust collection and analysis of data, assessing morphological development and changes in sediment storage (and gravel flux) in the system as a whole.

4. A Framework for practice

4.1 Allowing room for the river to move

A strategic change in the direction of river management - away from a 'command and control' ethos that has dominated practice for over half a century and proving to be unsustainable (particularly in the light of forecast climate change and associated shifts in flood magnitude and frequency), towards a 'living with the river' ethos - is multi-generational in scope and incorporates Te Mana o te Wai (Section 4.2.1). This framework for practice may be embedded in an even broader planning approach such a Floodplain Management Plan. It is simply unfeasible to walk away from river corridors with the infrastructure and investment and livelihoods that are bound up with the current practice of 'control'. A phased approach is needed and communities will need time to appreciate and understand the changes in practice.

Initial community resistance is probably to be expected: why can't current practice continue? The answer is that there is a price when attempting to constrain dynamically adjusting rivers. Channels could be rock-lined to keep them in place, but the cost of rock lining is $333 per linear metre and rivers tend to undermine or bypass rock lining. To avoid lining from becoming outflanked by the river requires constant intervention and extension of linings or other bank protection or mechanical intervention (e.g. constructing bypass channels). In addition, lining a channel with rock disconnects the channel from its floodplain, which is an important source of sediment (including gravel). The resulting sediment deficit tends to promote bed incision, further destabilising banks and isolating bar surfaces from mobilising flows. There is also a price to pay in terms of reduced habitat diversity. Rock-lined channels tend to become single-thread, because the channel digs down at the rock interface since energy that was previously used to erode a bank and transport sediment is now focused on the channel bed at the rock margin.

A far more sustainable alternative to rock lining is to allow the dynamically adjusting river to dynamically adjust: let the river be a river and do what rivers do. Long-term this is likely to be the more financially prudent option, although initial costs will be required if land is to be purchased for retirement from production and return to the river. Allowing the river room to erode will increase the geomorphic and habitat diversity in the river corridor. Removal of bank protection in narrowed channels provides the opportunity for lateral channel migration and bank erosion, which provides accommodation space for bar complexes and opportunities for in-stream wood to create forced scour holes and riffles, such changes have been observed in a Scottish Highland river that would not be out of character in Southland (Williams et al., 2020) (Figure 13).

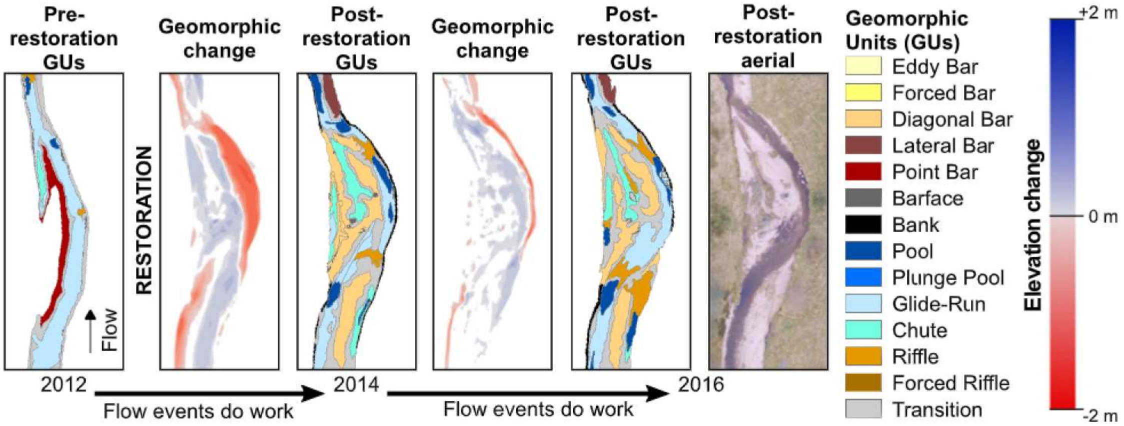

Figure 13. Channel changes and increased geomorphic and habitat complexity in a reach of the Allt Logy, Scotland where removal of bank protection has increased accommodation space in the active channel (source: graphical abstract, Williams et al., 2020).

Allowing rivers more room to adjust also improves resilience in the face of increased flood magnitudes. Larger floods, occurring more frequently will require more room to be accommodated. It is better to accept this reality than endeavour to keep a river constrained in a corridor which is simply too narrow to contain it. A widened corridor allows for bank erosion and bend migration, and cutoff, and braid development. A widened corridor accommodates larger floods, which can happen without resulting in significant losses to land, infrastructure and even life, or substantial change to the form of the river, which is much better adjusted to accommodate large floods and does not require intervention to 'fix', because the natural processes of erosion and deposition within the river corridor enable the river to fix itself.

The key opportunities to implement a widened corridor framework arise during flood events, but this must be predicated on the community realisation that ES are not going to jump straight back into the river to push it back to its pre-flood position. The community needs to be prepared for this action (or inaction) before the next large event. Floods are when the river will naturally adjust and mapping of the floodplains and modelling flow and sediment dynamics will be able to provide some clarity as to where a river is likely to adjust to during a flood of a given magnitude. This scenario is not to imply a free-for-all for the river, but rather a better accommodation of river processes and their interaction with the floodplain. Inevitably there will still be lines drawn on a map, but their location can give better effect to river processes and floods.

An approach of phased withdrawal flood-by-flood would see progressive improvements of room for the river in the active river corridor over time. Flood damage of critical infrastructure will need to be repaired, but longer term less infrastructure would be located where it conflicts with natural processes in the river corridor.

4.2 Stakeholder engagement and paradigm shifts

Approaches to gravel management should be negotiated with key stakeholder groups, notably iwi and hapu, Fish & Game, DoC, and local landowners represented by catchment committees. Best practice in river management is to work with the river and to bring stakeholders and community groups to an informed understanding of this practice. To be successful, a gravel management policy needs to be sustainable and build resilience in Southland's river environments. The conceptualisation of a resilient river as one with e.g. '500 year' flood protection, able to withstand the worst that nature throws its way fails to recognise river systems as dynamically adjusting entities in the landscape, and fails to recognise that people are part of the riverscape. A resilient riverine environment incorporates both the river channel and its floodplain and the people who live / work on that floodplain. In the 21st century community resilience to changes in flood magnitude and frequency is built by learning to live with rivers, rather than defend against them by building ever larger stopbanks or lining channels with rock. This will inevitably involve a paradigm shift in the way river management is both done and communicated. An informed, participatory approach is needed to ensure the communities alongside Southland's rivers understand how and why the approach being adopted is needed and appropriate. This will take time and patience.

4.2.1 Te Mana o te Wai

Te Mana o te Wai is about restoring and preserving the balance between water bodies, the wider environment, and the community—protecting the mauri of the wai; the integrated and holistic well-being of a freshwater body (Te Aho, 2019). Upholding Te Mana o te Wai acknowledges and protects the mauri of the water. This requires that the use of water also provides for Te Hauora o te Wai (health and mauri of the water body), Te Hauora o te Taiao (health and mauri of the environment), and Te Hauora o te Tāngata (the health and mauri of the people), including concerns for mahinga kai (gathering of food that is safe to eat), and protection of Wai Tapu (Sacred Waters). The National Policy Statement for Freshwater Management includes Te Mana o te Wai, explicitly recognising that protecting the health of freshwater protects the health and well-being of the wider environment (Te Aho, 2019).

A strategic policy for gravel management in Southland should be co-designed with iwi and give effect to the principles of Te Mana o te Wai. This entails working with tāngata whenua and communities to set out long-term visions in regional policy statements and plans (such as catchment-specific Floodplain Management Plans), which prioritise the health and wellbeing of rivers, then the essential needs of people. Rivers are conceived through ancestral connections and relations, whereby people live with, as a part of, the environment, rather than managing it per se (Brierley et al., 2022). For Māori, an awa is not just a resource to be used. Rather, it is an interconnected, living system—a force to be lived with, reckoned with, and respected (*te awa tupua*) (Muru-Lanning, 2016, SALMOND, 2014). This reciprocal relationship innately frames *manaaki whenua* (caring for the land) alongside *manaaki tangata* (caring for people). Custodial linkages and responsibilities are expressed through *kaitiakitanga* (inter-generational guardianship). If interdependencies falter or fail, loss or destruction engenders a state known as *mate* (ill-health, dysfunction). Its contrary, ora, is a state of peace, prosperity and well-being for people, plants and animals, as well as the river (Hikuroa et al., 2021).

5. Fine Sediment

Although fine sediment is not the focus of this report, fines have a role to play in contributing to stability of gravel beds, either by mortaring armour, or by providing a more suitable substrate for vegetation to colonise. Fine sediment management should be considered in a gravel management strategy, and this reflects the need to understand catchment sediment sources because besides being re-worked from the river bed and banks, the primary source of fine sediment likely reflects catchment soil erosion. Ultimately there is a need to know where a river gets its sediment from and what calibre of sediment this is. Assessment of erosion sources at a catchment scale can utilise a combination of erosion mapping and connectivity modelling, to understand where sediment is being generated and the likelihood of that sediment being delivered to a given point in the river channel / network. A modelling approach has been adopted by Manaaki Whenua Landcare Research (MWLR) in developing and deploying SedNetNZ, which spatially distributes budgets of fine sediment in the landscape (Dymond et al., 2016). SedNetNZ incorporates a range of erosion processes, including landslide, gully, earthflow erosion, surficial erosion, bank erosion, and flood-plain deposition. Application of SedNetNZ could be deployed in Southland, along with catchment-wide mapping of erosion and assessment of connectivity to fully understand sediment sources, and understand where erosion treatment should be best targeted (see Dymond et al., 2016).

6. Recommendations

Gravel budgets need to be developed in each river where gravel needs to be managed. The approach to developing these budgets should move away from cross-section and MBL analysis in favour of 3D topographic surveys of the active channel using bathymetric LiDAR.

A 5-year frequency of LiDAR river corridor survey is probably realistic, since this is sufficiently frequent to identify problems / issues, and in such long rivers, able to capture gravel conveyance effectively using a morphological budgeting approach.

Critical or sensitive sites (and trials) could be monitored on an event basis using drone SfM photogrammetry or drone-mounted LiDAR to generate elevation models. Subaqueous morphology may need to be captured using image analysis, with some ground survey for ground truthing – all SfM should include ground-control points surveyed with high accuracy and precision so that meaningful comparisons can be made between surveys and morphological budgets given some degree of confidence.

Present river geomorphology should be classified and compared with historic river morphologies using an NCI approach where aerial photographs of the river corridor prior to direct management are available. This allows original baselines to be properly understood and may set the direction towards longer-term river restoration, particularly if (selected) river reaches are to be given more room. An NCI assessment will help answer the question how much room a river needs in a given reach, and what type of behaviour may be expected (e.g. reversion to meandering or braiding).

A key question to understand is whether the rivers are locking up, and / or over-extracted. Gravel budgets will help address this.

Trials are advocated to assess the best approaches to deal with corridor choking – skimming, spraying, raking.

It should be noted that 'habitat ponds' are not natural features in the riverscape of Southland and create holes in the active channel that are disconnected from the river. Furthermore, extracting gravel from these holes likely contributes to any gravel deficit. Rivers simply do not scour such deep and extensive holes along their course.

Where gravel is required for aggregate, extraction beyond the river corridor using borrow pits is preferred, which in turn could be restored as wetlands and also potentially contribute to flood peak attenuation. Alternatively sustainable extraction (i.e. which does not exceed supply and where otherwise the river would continue to aggrade) may be appropriate in natural gravel sinks in the deposition zone in distal reaches (i.e. at the gravel-sand transition). Where gravel is transported to the coast, any extraction along the length of the river risks resulting in coastal sediment deficits and commensurate risks of coastal erosion.

A Strategic Gravel Management Plan needs to be supported by practice, informed by Environment Southland's partnership with iwi and engagement with community. The plan also needs to inform Council's plans and policies that contain a long-term vision, an approach for enabling the rivers to have more room, and a plan for how to transition from 'command and control', towards a 'living with the river' ethos.

6.1 Challenges of climate change & floods

Changes in flood magnitude and frequency are important to consider. Increased frequency of flows above gravel transport thresholds will naturally improve gravel conveyance. Bigger floods forecast may help resolve the locked river corridor problem, but larger floods will require more room and channel expansion is to be expected and must be anticipated. Channel expansion will recruit more gravel from secondary sources (i.e. floodplain and within the active channel). Southland rivers are likely to become more active.

However, climate change is not just predicting bigger floods, but also more intense droughts. This situation may mean are less predictable river behaviour in the region and management practices may need to adapt accordingly. For example, in flood-rich phases, or following significant singular flood events, it is advisable to let the river do the work to reset itself. Conversely, during flood-poor phases gravel conveyance is likely to be reduced and corridors could re-lock and the gravel become more embedded. To manage the trajectories and responses of Southland's rivers requires a strategic investment in appropriate monitoring programmes, so that river behaviour can be properly understood, rivers treated as the dynamic entities they are and lived and worked *with*, rather than worked and defended *against*.

Acknowledgements

Thanks to Paul Pollard and Randal Beal for the opportunity to present this report and for discussions with ES, DoC and Fish & Game staff to date.

Professor Ian Fuller
5 December 2023

Appendix 1: Technical recommendations for gravel extraction[3]

1. The need for Technical assessments of gravel extraction

Extraction of gravel from the active river channel (dry bars and wetted channel) has a direct impact on the physical characteristics of the river, notably changing channel morphology: geometry, shape, bed elevation, stability; sediment: composition, stability, transport and turbidity; and flow properties: stream power, velocity. These characteristics comprise the physical habitat parameters of a stream. Alteration of physical habitat parameters in turn can have significant impacts on instream biota. Technical assessments of the potential and actual impacts of gravel extraction should be undertaken with a view to understanding the physical structure of the river, i.e. channel morphology, sediment and flow regime, paying careful attention to sediment flux within the river system as a whole, as well as discrete behaviour of reaches being considered for gravel extraction. This physical structure of the river provides the template for river habitat.

2. Requirements for technical assessments

It should be demonstrated that extraction will be within natural supply flux (based on a quantified sediment budget). This initial sediment budget should make use of the longest possible records of sediment flux available for the extended section of river in which extraction is to take place. It is anticipated that this will make use of available river cross sections and bed level data obtained in the past, as well as repeat 3D surveys of the river corridor using bathymetric LiDAR and (locally) Structure from Motion photogrammetry obtained recently and into the future. Long-term and large-scale trends in sediment flux should be identified to provide a thorough context for extraction at any given site.

A detailed geomorphological assessment of extraction sites, as well as adjacent reaches upstream and downstream, should be provided to characterise and contextualise channel forms and structure. Bedload sediment in the site should be characterised by detailing the nature of the surface sediment and its variability in the reach, as well as the nature of the subsurface sediment, which will be exposed by removing the natural armour layer during the extraction process.

Where deemed feasible and necessary, the intended approach to gravel extraction must seek to minimise adverse effects on river channel morphology, sediment, flow and therefore habitat. The quantum of gravel to be extracted and the timeframe over which extraction will take place and the likely impacts on channel morphology, sediments and flow should be anticipated. A management protocol for fine sediment left behind in any extraction process should also be detailed.

3. Recommended best practice guidelines for gravel extraction

Site sensitivity to extraction must be assessed by taking into account trends in river bed levels and morphological changes in the river as a whole and more specifically at, and in the immediate vicinity of, the extraction site. Changes in bed level and channel morphology should be informed by existing bed level data from cross-section surveys and aerial photographs for the extended river) and a more detailed sediment (morphological) budget for the site and adjacent reaches. Morphological budgeting using a DEM of difference (DoD) between repeat 3D surfaces of the active river channel should be used in future as these datasets become available.

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[3] Based on Fuller, I.C. & Death, R.G. (2021) Gravel Extraction Habitat Advice, Report for Horizons Regional Council.

Review gravel allocation at a timeframe in accord with data acquisition (maximum 5 years) and issue authorisations for extraction for a period within the timeframe of data acquisition to a stipulated maximum volume informed by the site-specific gravel budget. To ensure sustainable gravel management, the quantity of all material actually removed from the river should be the key factor measured (not the volume of gravel carted) because post-processed volumes will not necessarily capture the total volume of material removed. Submission of volumes extracted should be recorded monthly. The condition of the extraction site immediately before and immediately after extraction, as part of the assessment of river condition and the impacts of extraction on river geomorphology should be recorded using local, ground controlled Structure from Motion photogrammetry using drones. Gravel extraction should take place in a way which retains natural channel form, or which restores the site to a natural form, taking a morphologically-sensitive approach to extraction.

Best practice will ensure gravel extraction is informed by a properly understood, quantified sediment budget to ensure extraction is sustainable, i.e. matched by supply. This will be monitored on at least an annual, if not flood event basis at site, and a 5 yearly basis for a given river.

4. Recommended monitoring requirements for gravel extraction consents

Monitor sediment flux to ensure extraction remains within supply limits (point 3 above). This is best determined using a morphological budgeting approach, either using appropriately spaced channel cross-sections and/or Digital Elevation Models (DEMs) of the active river channel derived from ground survey and/or photogrammetry and/or LiDAR. A morphological approach will also serve to monitor channel form / geometry to ascertain whether extraction is having any deleterious effects (incision, width:depth ratio changes etc) upstream and downstream of the site.

The spatial extent of morphological monitoring should be scaled according to channel size, and this may also determine which approach is most suited to use. At a given site the frequency of monitoring should be at least annual in addition to immediately following significant (i.e. channel forming) floods, normally of a $Q_{2.33}$ magnitude or larger.

Surface and subsurface sediments should be monitored, focusing on the adjacent upstream and downstream reaches being used to assess the sediment flux and morphology. Sediment characteristics should be monitored at least annually in addition to immediately following significant (i.e. channel forming) floods, normally of a $Q_{2.33}$ magnitude or larger during which significant sediment movement is likely to take place.

Monitor fine sediment and assess the impacts of the extraction site by monitoring upstream and downstream suspended sediment loads to quantify the effects on suspended sediment by extraction. If a significantly adverse effect is detected, mitigation should be reviewed and a strategy implemented to offset these effects.

A Habitat Quality Index (HQI) at the site scale, and a Natural Character Index (NCI) at a reach scale (upstream and downstream of extraction) should be used to assess any changes in habitat associated with the gravel extraction (Death et al., 2017; Fuller et al., 2020).

Appendix 2: Reviewing impacts of gravel extraction on river habitat and stream health[4]

The geomorphic impacts of instream gravel extraction are summarised conceptually in Figure A1. This review is necessarily informed by drawing upon international literature, as detailed research on the impacts of gravel extraction in New Zealand rivers is limited (Holmes, 2017). Nevertheless, efforts are made to draw comparisons between river types more representative of those found in New Zealand.

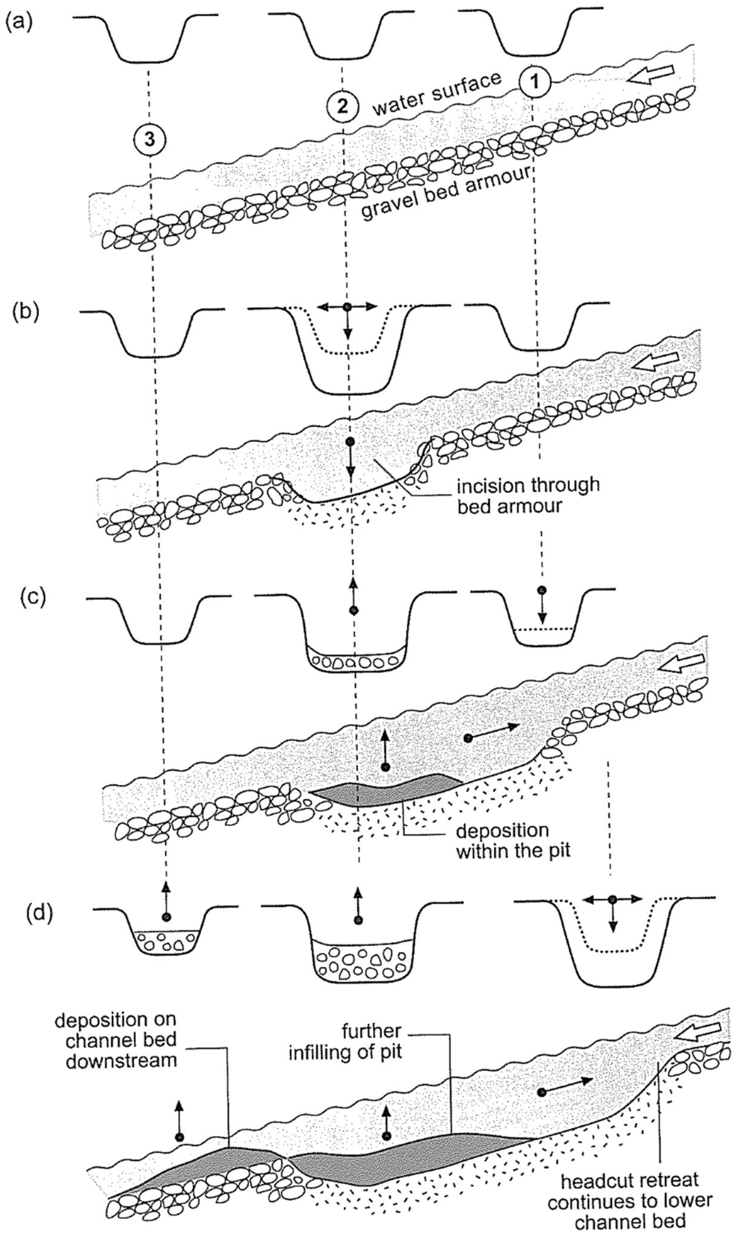

Figure A1. Geomorphic impacts of in-channel gravel extraction. *(a) Pre-extraction*: sediment load and available force to transport sediment are continuous through the reach. *(b) Excavation* breaks the bed armour and initiates head-cut of the extraction site – at this point the pit captures sediment, interrupting sediment transport downstream as the river retains sediment transporting capacity, but has no sediment to transport, which leads to (c). *(c) Headward extension* of headcut proceeds to maintain bed surface slope, while hungry water Kondolf (1997) erodes the downstream end of the extraction site given the sediment deficit induced by (b). *(d) Sediment released* from (c) partially infills the incised and expanded extraction site. Note: since extraction breaks the armour, the underlying finer substrate is most readily mobilised, generating fines which subsequently clog gravel interstitial spaces downstream.

(sourced from Fig 13.7 Fryirs & Brierley, 2013).

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[4] Based on Fuller & Death (2021)

Figure A1 is based on seminal work on the subject by Kondolf (1994). It is important to recognise that extracting gravel from the active channel (wetted channel and adjacent channel bars set between banks) causes bed degradation (Downs and Gregory, 2014). Gravel extraction tends to focus on those rivers that by nature are more dynamic and laterally active because these rivers have the energy to transport gravel and because gravel-bed rivers are usually set between non-cohesive or composite banks, which offer less resistance to erosion than cohesive banks typical of finer-grained river types. Furthermore, gravel extraction often takes place under the pretext of river management in an effort to control or mitigate these dynamic adjustments. Lateral displacement of gravel-bed rivers is a normal part of the way these rivers function (Church, 2015). In turn, any intervention in the active channel is likely to promote a response given the naturally dynamic nature of these systems, and that any activity in, or adjacent to the active channel must be ready to accommodate lateral channel adjustment. Even when gravel is extracted from ‘borrow pits’ on the adjacent gravelly floodplain, there is a risk of channel migration into these pits during large floods, promoting rapid channel avulsion of powerful rivers (River, 1998; Rinaldi et al., 2005; Mossa and Marks, 2011). Downs and Gregory (2014) note that upstream bed degradation causes channel incision, undermining of upstream structures (bridges etc), changes to bed sediment composition that reduce fish spawning habitat (due to release of fine sediment, cf. Figure A1), as well as potentially lowering water tables and damaging riparian vegetation (Kondolf, 1997; Kondolf, 1994; Erskine, 1998). An Australian study in the Hawkesbury-Nepean River, NSW (Erskine, 1998), identified 13 physical impacts and 14 biological impacts directly attributed to extractive industries on the river (Table A1).

Table A1. Environmental impacts of extractive industries in the Hawkesbury-Nepean River, NSW (Erskine, 1998), cited in Downs and Gregory (2014). Not all of these impacts would be expected to occur in the higher-energy rivers in Southland, less likely effects have question-marks.

Physical impacts	Biological impacts
Bed degradation	Loss of macrophytes, emergent and riparian vegetation
Increased water depths	Weed invasion
Channel widening	Water acidification?
Bank erosion	Fish kills?
Channel enlargement	Mycotic fish diseases?
Channel avulsion	Thermal, oxygen and salt stratification?
Turbidity plume	Reduced plant uptake of nutrients
Bed armouring	Reduced light penetration
Mud deposition on bed	Water quality barriers to fish migration
Changed hydraulics	Loss and fragmentation of riparian corridor and aquatic habitat
Changed estuarine salinity?	Reduced diversity of aquatic habitat
Pyrite oxidation?	Loss of wood / woody debris
Changed sediment transport patterns	Reduced abundance of native fish
	Increased abundance of exotic fish

To take a more wide-ranging, international perspective on the impacts of gravel extraction on river habitat and stream health, Table A2 summarises the range of possible physical effects of gravel mining on alluvial channels, reviewed by Rinaldi et al. (2005) and updated.

Table A2 Summary of the possible effects of sediment mining on alluvial channels, based on Rinaldi et al. (2005) and updated.

Main types of physical effects	Selected references
Upstream incision (headcutting along main river and tributaries)	Lane (1947), SATÔ (1971), Sato (1975), Scott (1973), Bull and Scott (1974), Lagasse et al. (1980), Galay (1983), Collins and Dunne (1989), Kondolf (1994), Kondolf (1997), Sandecki and Avila (1997), Surian and Rinaldi (2003), Marston et al. (2003), Martín-Vide et al. (2010), Rascher et al. (2018), Llena et al. (2020),
Downstream incision	Galay (1983), Brookes (1988), Sandecki and Avila (1997), Rinaldi and Simon (1998), Rinaldi (2003), Martín-Vide et al. (2010), Wyżga et al. (2012), Le Lay et al. (2013), Hajdukiewicz et al. (2016), Llena et al. (2020),
Infrastructure impacts (e.g. bridges)	Kondolf (1997), Sandecki and Avila (1997), Piégay et al. (1997), Rinaldi and Simon (1998), Surian and Rinaldi (2003), Marston et al. (2003), Uribelarrea et al. (2003)
Channel instability (lateral changes, width & morphology: e.g. planform change, narrowing)	Petit et al. (1996), Bravard et al. (1997), Wyżga (2001), Surian and Rinaldi (2003), Rinaldi (2003), Martín-Vide et al. (2010), Wyżga et al. (2012), Scorpio et al. (2015), Le Lay et al. (2013), Serlet et al. (2018), Rascher et al. (2018), Llena et al. (2020),
Bed armouring / coarsening	Lagasse et al. (1980), Zawiejska et al. (2015),
Channel capture or avulsion by floodplain pits	Kondolf (1997), River (1998), Mossa and Marks (2011)
Effects on frequency of inundation	Wyżga (1997), Wyżga (2001)
Water table lowering	Hatva (1994), Mas-Pla et al. (1999)

A2.1 Morphological Effects: channel geomorphology and sediments

Upstream incision occurs when gravel extraction steepens the slope of the channel bed upstream of the extraction hole (cf. Figure A1). The bed-level lowering of the main channel also lowers the base-level of tributaries, increasing their slope and potential to incise. Downstream incision occurs where sediment supply is disrupted by extraction (cf. Figure A1). Gravel mining effects assessed in Venezuela López S (2004) indicated progressive degradation upstream and downstream of a gravel extraction site. Instream gravel mining has been recognised as one of the most important causes of channel degradation in South America (Arróspide et al., 2018).

Channel instability is often triggered by incision responses, because banks become undermined and prone to lateral erosion, especially as the hungry water potentially erodes sediment from the adjacent channel margins. However, longer-term extraction is now recognised as contributing to significant channel narrowing over time. In-channel sediment mining is believed as having significantly contributed to reduced sediment availability in the Tammaro River, Italy (among several other factors) that led to river bed incision and channel narrowing (Magliulo et al., 2021). Importantly, Magliulo et al. (2021) attribute a significant impact of sediment mining even though it was localised and lasted no more than 10 years between the 1980s and 1990s. However, it must be noted that narrowing and incision of the river was underway before sediment mining was recorded, driven by land use change (reforestation), increased precipitation and flood magnitude. It is therefore likely that gravel extraction exacerbated, but did not cause, narrowing and incision of the Tammaro River. Nevertheless, this example demonstrates the potential sensitivity of river systems to localised, and short-lived extraction. Similar findings in the Trebbia River (northern Italy), i.e. narrowing and incision in response to sediment mining alongside dams observed by Bollati et al. (2014), as well as in the Scrivia River, also northern Italy (Mandarino et al., 2019a; Mandarino et al., 2019b). In another northern Italian river, the Orco River, Brestolani et al. (2015) observed a range of effects included bank instabilities, as well as incision. These examples from northern Italy can be taken as representative of the behaviour of dynamic, wandering and braided gravelly rivers in New Zealand, i.e. short, steep, with flashy discharge regimes and a natural abundance of coarse bedload.

Elsewhere, similar high-energy rivers draining the Carpathian Mountains in Poland deeply incised during the 20th Century in response to increased transport capacity of these rivers, attributed to channelisation and associated reduction in sediment to the channels, which was enhanced by in-stream gravel mining (Wyżga, 2007). In Nepal, gravel extraction has been attributed as the cause of bank erosion, slope instabilities, river incision, headcutting in the Tinau River (Dahal et al., 2012).

In the Polish Carpathians, a study by Zawiejska et al. (2015) has shown that extraction of larger particles from the channel bed facilitated entrainment of exposed finer grains (cf. Figure A1). This resulted in rapid degradation of the bed and channel incision. This incision concentrated flood flows in an increasingly narrow and deep channel, which increased flow competence that transported coarser particles than previously typical, essentially flushing coarser bed material from the incising river section. This example demonstrates the complex relationship between the morphological effects of gravel extraction at site, and potential downstream consequences for both channel morphology and sediment conveyance. The river studied (Czarney Dunajec) displays remarkably similar characteristics to gravel-bed rivers in Southland (Figure A2).

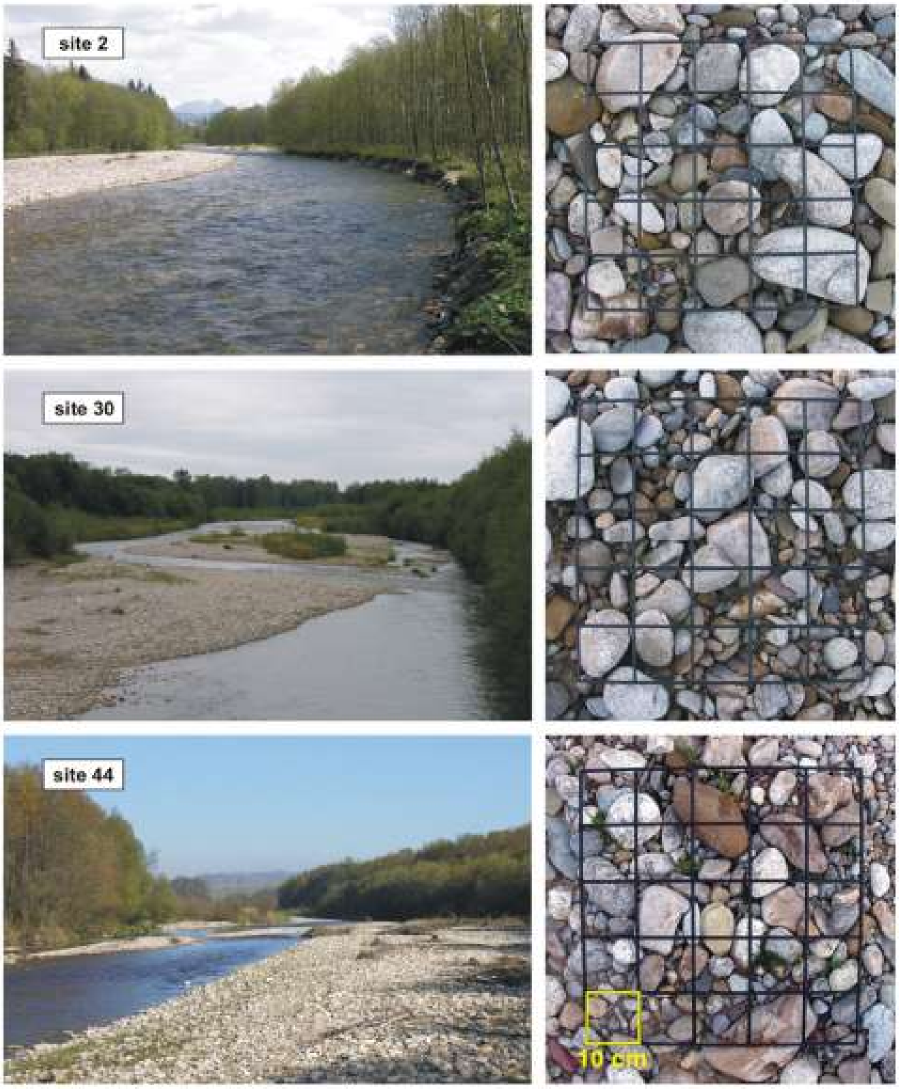

Figure A2. Views of unmodified reaches of the Czarny Dunajec River (Polish Carpathians) (Zawiejska et al., 2015).

The impacts of gravel extraction on sediment transport have also been reported by Béjar et al. (2018) working on the upper Rio Cinca, which drains the Spanish Pyrenees. In this mountain river, Béjar et al. (2018) observed an increase in suspended sediment transport downstream of gravel extraction, due largely to mobilisation of finer substrate exposed by the removal of the coarser armour layer.

A2.1.1 Complex response: wet and dry extraction

The effects of gravel extraction on river sediment are complex, and may depend on the approach to extraction. For example, mining from the wetted channel creates channel pits (as depicted in Figure A1) and release of finer substrate may smother downstream reaches with sand/silt (Downs and Gregory, 2014). As finer sediment is selectively outwashed from the bed material, an armouring effect can also be observed (Rinaldi et al. 2005).

Extraction from dry bar tops may also leave behind large volumes of fine sediment, which is subsequently washed into the channel by higher flows, leading to a similar smothering effect (Figure

A3). Bar top skimming also removes the coarsest sediment, which can enhance bedload transport and, accordingly, channel instability and propensity for adjustment (incision and lateral erosion) (Kondolf, 1994; Rinaldi et al., 2005). As noted by Holmes (2017) and a review by Packer et al. (2005) dry riverbed extraction potentially creates a wide, flat channel geometry at the site of extraction (cf. Figure A3), which reduces the definition of low flow channels and in turn increases channel instability (Kondolf et al., 1994; 1997). Extraction replaces well-defined pool-riffle sequences with homogenous runs (Downs and Gregory, 2014) and flattening of the active channel relief removes side or chute channels where present. In contrast to observations indicating enhanced bedload transport (Kondolf, 1994; Rinaldi et al., 2005), it is also possible that the extraction site in its over-widened form has a reduced sediment transport capacity resulting in deposition at the site (Kondolf, 1998). However, while the extraction pit (lowered site surface) may infill, the bed level of the extracted reach has been lowered, which can propagate headcutting and upstream incision (cf. Table A2). Furthermore, deposition of sediment at the extraction site may generate hungry water downstream because sediment has been trapped at the extraction site, leading to channel degradation downstream (Kondolf, 1994; 1997).

Figure A3. Flattening of the active channel and generation of excess fine sediment (sand/silt) from dry, bar-top extraction, Raumai, Pohangina. Photos: RGD

A2.1.2 Hydrological effects

The effects of channel incision can also have unintended hydrological consequences because incised channels have an increased flood conveyance capacity. This means that flood flows that would have overtopped banks and dispersed across the adjacent floodplain are now retained within the deeper channel. This may be the desired effect if mitigation of flood hazard is in mind, but as Rinaldi et al. (2005) recognise, these benefits are not always effective because flood waves are no longer attenuated by overbank flows and are in fact enhanced downstream, increasing stream powers and the potential for greater channel instabilities and incision.

Bed degradation of incised channels may also result in lowering of the local water table that is hydrologically connected to the river (Rinaldi et al., 2005). This effect in turn can lead to drying of adjacent floodplain wetlands (Packer et al., 2005), as well as damage to riparian vegetation (Kondolf, 1994).

A2.1.3 Consensus – application to New Zealand

The consensus drawn from the international literature (Table A2) is that essentially gravel extraction may have significant effects on the physical characteristics of river channels. In turn, by having such profound effects on the structure of the river, the physical template for river habitat is significantly altered, with a reduction in both quality and quantity of habitat for instream biota (Rempel and Church, 2009; Holmes, 2017).

The precise morphological and sedimentological response of a river to gravel extraction, is however complex, reflecting discrete site conditions including channel morphology, dimensions and sediment flux. Kondolf (1994) does refer to the potential benefits of instream gravel extraction for river control. Interestingly he refers to a New Zealand example, specifically the Waimakariri River, which transports ~150,000 m^3 of bedload annually (Carson and Griffiths, 1989) and is aggrading in its lower reaches. Extraction in this aggrading reach has maintained the river in its present course and prevented otherwise likely avulsion through or towards Christchurch. However, Kondolf (1994:240) goes on to observe, "Rivers experiencing rapid aggradation, such as the Waimakariri, are less common than rivers experiencing degradation due to a gravel deficit. Even in New Zealand, with high bedload sediment yields…there are more reports of rivers with degradation problems (from instream mining…) than rivers with aggradation problems…" Kondolf then cites a series of unpublished reports from the 1970s and 1980s (Pemberton, 1974; Williman 1977; Anonymous 1985; 1986). He also refers to the work on the Manawatu by Page and Heerdegen (1985), who observed a degradation of the riverbed particularly in the vicinity of Palmerston North, but more generally between the gorge and Opiki, which they attributed to gravel extraction exceeding supply and channelisation, reducing replenishment of sediment via bank erosion. The behaviour of this part of the Manawatu must in turn be contrasted with the aggradational trends at Opiki, beyond which the river lacks competence to transport gravel load, as well as the rapid aggradation in the throats of SE Ruahine headwater streams, such as the Tamaki, attributed to catchment disturbance in the 1970s (Fuller et al., 2016; Mosley, 1978; Schumm, 1977).

More recently, Kelly et al. (2005) have compiled information on the rates of gravel extraction from rivers throughout New Zealand (Figure A4). They note that over-extraction of river gravels can lower the riverbed, alter the channel profile and sediment composition, which they observe has threatened bridge piers in the Oreti River, Southland where, along with rivers in Nelson (e.g. Wairoa/Waimea) and elsewhere in Southland, which have limited gravel supply rates, past extraction has exceeded supply and channels have degraded. Kelly et al. (2005) observed significant morphological and sedimentological impacts in the Kakanui (near Oamaru) as a result of sediment starvation (extracting ~32,000 m^3 of sediment). Compared with upstream reaches, the river at and downstream of the extraction site is significantly narrower, more incised, with a finer substrate (more silt and sand), as well as having higher and more uniform flow velocities. Where gravel extraction has been managed in response to channel degradation and threated infrastructure in the Wairoa/Waimea in Nelson, Kelly et al. (2005) report the primary trend is a diminished grain size of bed material downstream, with channel dimensions and water velocities relatively unchanged. Williams (2011) observes that extraction of gravel bed material where reaches are not naturally aggrading in natural depositional zones within a catchment (normally coastal depositional plains) generally gives rise to channel degradation.

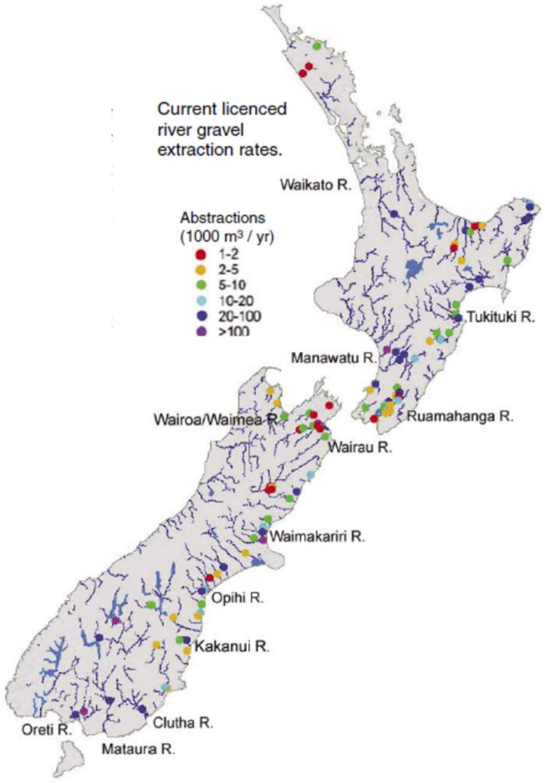

Figure A4. Licenced river gravel extraction sites in New Zealand, with abstraction rates identified. Source: Kelly et al. (2005).

A2.2 Ecological effects

Gravel extraction from the active channel destroys in-channel features (e.g. riffles, pools), which are important for habitat diversity (Rinaldi et al., 2005; Tunnicliffe and Baucke, 2021). An extended period of ongoing gravel extraction in the Ngaruroro River is attributed as the cause of reduction in habitat heterogeneity in that river (Tunnicliffe and Baucke, 2021).

The impact of gravel extraction affects fish in several ways. Large-scale and long-term gravel extraction alters habitat and hydrodynamic characteristics of rivers, which may impact fish distribution in some contexts (Freedman et al., 2013). Gravel extraction tends to reduce habitat heterogeneity as natural pool-riffle sequences are replaced by continuous pools or runs. Certain species will likely be more affected than others, e.g. blue gilled bullies require riffle habitat. Freedman et al. (2013) worked on North American streams where they found lotic species displaced by lentic species and generalist and invasive species displaced native habitat specialists. Destruction of islands and bars in wandering and braided rivers, as well as removal of wood in the course of sediment extraction reduces morphologic and hydraulic diversity of the river, with further habitat loss (Rinaldi et al., 2005).

The diversity of invertebrate communities in flowing waters is partly a function of habitat heterogeneity along the riverbed (Kelly et al. 2005). Microhabitat diversity is increased by larger, more heterogeneous bed sediments that can be used by colonising invertebrates and fish, furthermore larger substrates are more stable, offering refugia in higher flows. Conversely, finer-grained beds are smoother and provide less diversity and refugia, and are also more likely to move even under lower flow events (Kelly et al., 2005). The impact of the changes to sediment described in the Kakanui River in section A2.1.3 have had a knock-on effect on stream biota. Kelly et al. (2005) report that concurrent with a fining of bed material downstream of extraction, there was a decline in total invertebrate abundance, taxon richness and percent composition by sensitive taxa such as mayflies, stoneflies and caddisflies (%EPT) (Figure A5). In contrast, in the Wairoa/Waimea effects on %EPT were less severe, although still evident (Figure A5).

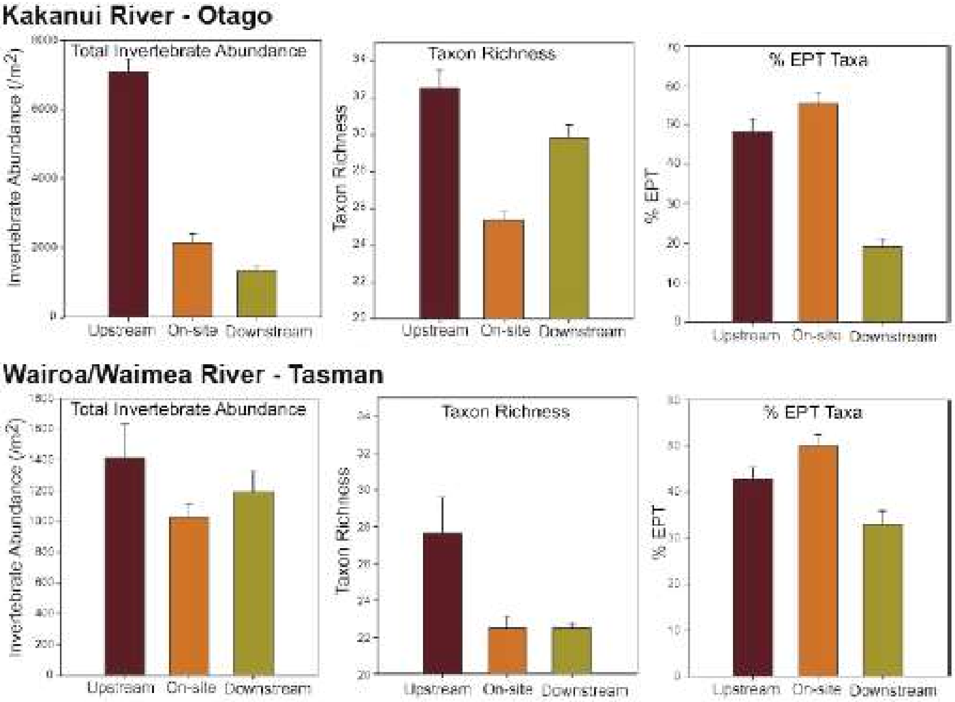

Figure A5. Benthic invertebrate abundance, taxon richness (number of species) and %EPT of benthic communities sampled upstream, on-site and downstream of gravel extraction operations in the Kakanui and Wairoa/Waimea Rivers (source Kelly et al., 2005).

An increase in deposited fine sediment is the adverse outcome of gravel extraction that has the potential to have the greatest impact on instream biology (Figure A6). Maintaining low levels of deposited fine sediment is critically important for maintaining ecosystem health in rivers (Ryan, 1991; Waters, 1995; Matthaei et al., 2006; Townsend et al., 2008; Clapcott et al., 2011; Collins et al., 2011). Appropriate deposited sediment levels to maintain ecological health of rivers and streams in New Zealand based on river type are clearly laid out in Table 16 of the NPSFM. These values are based on a comprehensive study by (Franklin et al., 2019) using all the currently available data for New Zealand.

Death et al. (unpublished) investigated the impact of gravel extraction from dry beaches, alongside the wetted channel in the Pohangina River, Manawatu, in the summer of 2010/2011. Large quantities of fine sediment on beaches were mobilized into the wetted channel following the first significant rainfall event (Figure A6). Invertebrate communities changed from being numerically dominated by mayflies and caddisflies upstream to chironomid dominated communities downstream after gravel extraction and a high flow event. There was a corresponding decrease in biological indices such as MCI and percent EPT (Figure A7). This suggests gravel extraction from dry beaches can have quite severe detrimental impacts on instream ecological integrity as a result of high levels of deposited fine sediment.

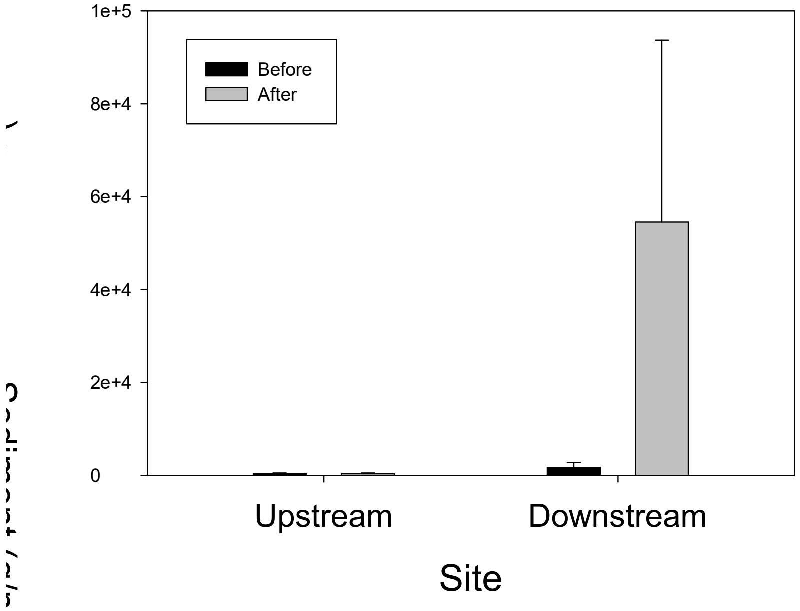

Figure A6. Deposited fine sediment measured in five replicate Quorer samples at sites before and after, upstream and downstream of dry channel gravel extraction in the Pohangina River 2010.

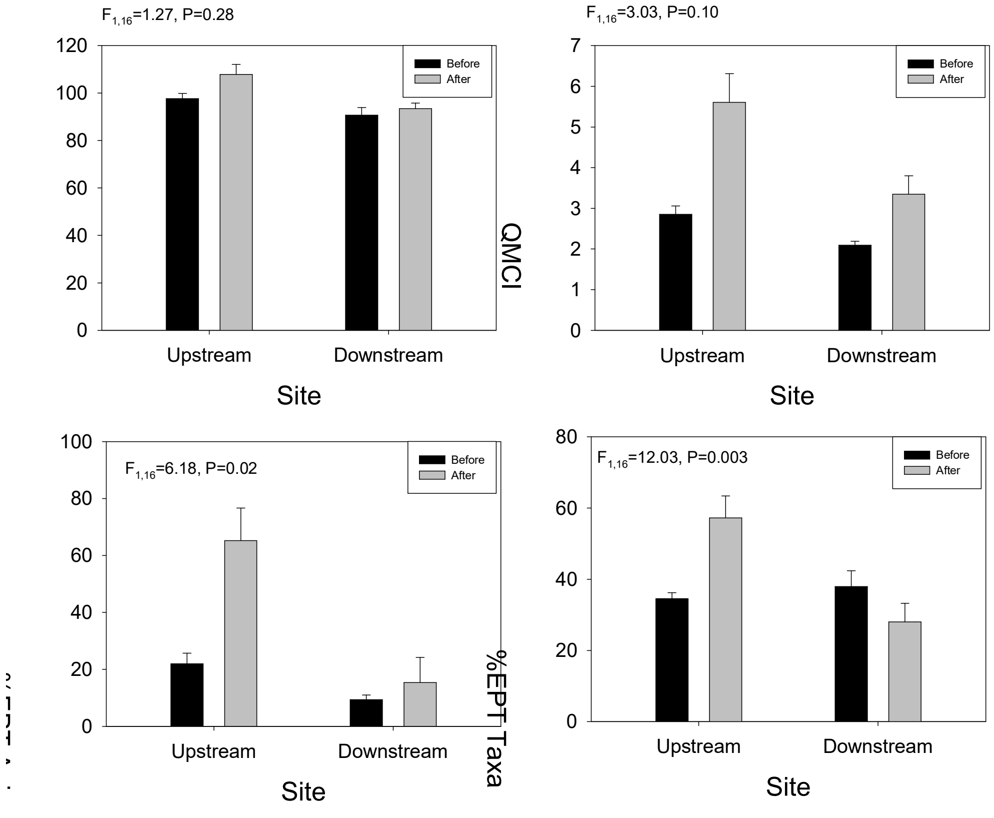

Figure A7. MCI, QMCI, %EPT taxa and %EPT animals collected in five replicate Surber samples at sites before and after, upstream and downstream of dry channel gravel extraction in the Pohangina River 2010.

Sediment is a component of natural aquatic systems, which is transported as suspended sediment and bedload, mostly at times of high river flows and floods. Small particles, such as clay and silt, are generally transported in suspension, whereas larger particles, such as sand and gravel, usually roll or slide along the riverbed. Increased levels of fine suspended and deposited sediment can have dramatic effects on stream ecosystems. Increased sediment loads can:

- smother natural benthos;
- reduce water clarity and increase turbidity;
- decrease primary production because of reduced light levels;
- decrease dissolved oxygen;
- cause changes to benthic fauna;
- kill fish;
- reduce resistance to disease;
- reduce growth rates; and
- impair spawning, and successful egg and alvein development.

Deposited sediment can smother animals directly (Figure A8A and A8B) and/or motivate them to leave. It can also smother and bind with the periphyton on rock surfaces that is the food for many aquatic invertebrates and lower the nutritional quality of this food. It fills in the interstitial spaces between rocks (Figure A8C) where many of the fish and invertebrates live during the day (most are nocturnal) or during flood events. Stream invertebrates and many fish (e.g. eels) can live at least up to a metre under the stream bed if there are suitable interstitial spaces (Williams and Hynes, 1976; Stanford and Ward, 1988; Boulton et al., 1997; McEwan, 2009).

Figure A8A. Koura struggling in deposited sediment.

Figure A8B. Banded kokopu struggling in deposited sediment.

Figure A8C. Stream substrate with interstitial spaces partly clogged with deposited sediment.

Fish, such as salmonids, that lay their eggs in the substrate of the stream are also particularly sensitive to deposited sediment. The sediment can smother eggs directly or reduce oxygen levels in the area directly below the stream bed dramatically (Olsson and Persson, 1988; Crisp and Carling, 1989; Weaver and Fraley, 1993; Waters, 1995). Generally less than 10% sediment cover is considered good for trout spawning and none is optimal (Clapcott et al., 2011).

Fish abundance and diversity in rivers in the North Island's East Coast Region were found to be negatively impacted by deposited sediment, rather than high suspended sediment loads per se (Richardson and Jowett, 2002). The smothering effect of silt-laden environments diminishes food supply for fish by adversely affecting macroinvertebrate abundance (cf. Figure A5). High silt laden environments also reduce spawning opportunities for some fish species (Tunnicliffe and Baucke, 2021).

Changes in macroinvertebrate communities occur when the deposited fine sediment levels starts to exceed 20% cover (Clapcott et al., 2011; Burdon et al., 2013). This research suggests an upper limit of 10 to 20% cover for deposited sediment, is appropriate for maintaining an excellent or good level of ecosystem health, respectively (Clapcott et al., 2011; Burdon et al., 2013).

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