Buffer Management– Benefits and Risks

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Executive summary

1. The management of rivers for flood prevention and maintenance of ecological health will need to accommodate potential future increases in the size and frequency of floods.
2. Strategies being adopted internationally to improve outcomes for river health and flood management include allowing the river more room to move under high flow conditions. This has the multiple benefits of reducing positive feed-back loops of river engineering, reducing flood risk and improving ecological health of the river and riparian surrounds. As a result there are financial, recreational, cultural and social benefits for tangata whenua and society in general.
3. The natural character, biological communities and water quality are all likely to benefit from a more natural geomorphological form.
4. Diverse and wide planted riparian buffers, in association with a more natural floodway will add to the above benefits.
5. There is the potential that some river sections may require continued and/or increased engineering work as the river adjusts from its current constrains to a more natural form. An adaptive monitoring and management strategy will be important to support this as the river evolves and avoid false assertions that giving the river more room is not working.
6. There is the potential for minor short term disruption but this should be weighed against the long term major benefits.
7. Riparian buffer planting alone may offer short term benefits, but it is not seen as a viable long term solution if the river channel is not also given more room.

Introduction

Climate change is altering global patterns of precipitation and temperature (IPCC, 2013), and is predicted to modify the occurrence of extreme climatic events, such as heavy rainfall and floods (Grantham, Merenlender & Resh, 2010; Aldous *et al.*, 2011; IPCC, 2013). In some regions, climate change is expected to increase the frequency, intensity, spatial extent and duration of large floods (Aldous *et al.*, 2011; Dankers *et al.*, 2014). The ability for engineering protection and remediation to cope with these more frequent and larger floods is increasingly being challenged (Klijn, Asselman & Wagenaar, 2018). In some regions, such as Europe and USA, river hydromorphology is now being naturalised to mitigate these flood effects and restore ecosystems (Hart *et al.*, 2002; Feld *et al.*, 2011; Klijn, Asselman & Wagenaar, 2018). New Zealand is just beginning to grapple with the competing demands of safeguarding people and infrastructure, whilst maintaining healthy river ecosystems in the context of the increasing frequency and severity of floods.

River engineers are beginning to consider softer approaches to protecting people and property that allow more natural river behaviour, maintaining and/or restoring connection with the flood plain and in some cases actually restoring river flood plains (Gostner *et al.*, 2013; Urbanic, 2014). Often however pressure from the public, politicians and insurance companies, and the large number of dwellings that are still built in active floodplains (Macklin & Harrison, 2012) mean the protection of biodiversity is given little or no consideration, even when both people and animals could be protected with a more forward-looking approach. In some regions of the world policies such as the EU Water Framework Directive (European Commission, 2000) are focused on improving riverine biological communities through more natural hydromorphology. The Foresight Report (Evans *et al.*, 2004; Evans *et al.*, 2008) and consequent policy changes in the UK and mainland Europe also stress working with natural riverine processes to mitigate for extreme flooding, but also to protect, restore and conserve riverine biological communities. This involves modifying riparian areas and floodplains, allowing for natural channel adjustment and encouraging large wood in some headwater streams (Sear & Arnell, 2006).

This report addresses current knowledge on a series of questions raised in considering a wider “room to move” strategy for managing flood risk and river ecosystem health in the Flood Management Plan, Te Kāuru, for the Upper Ruamāhanga.

Principally the report seeks to provide evidence or strategy to determine if the draft Te Kāuru Upper Ruamahanga Floodplain Management Plan (Te Kāuru) will improve the listed characteristics below:

- Natural character
- Aquatic life
- Water quality
- Erosion and sediment reduction
- Nutrient and phosphorus run-off reduction
- Contribution to social, economic and cultural wellbeing. There are some limitations that must be considered, such as:
- The location of existing assets such as bridges, roads and houses
- Balancing the environmental and cultural values with the costs of potential loss of productive land.

Current Floodplain Management

The Greater Wellington Regional Council have developed Floodplain Management Plans (FMPs) to manage flood risk from the Wellington Region's rivers and streams. The approach is to understand the processes affecting a river/stream and its floodplain within a wider catchment, and to provide a coordinated response through a FMP to reduce the impact of flooding and erosion. FMPs also aim to ensure any future development considers flood risk.

The outcome of a floodplain management plan process is a document that guides how the floodplain and catchment should be managed to:

- Minimise risks to life, health and safety
- Reduce severity of flood damage
- Promote sustainable use of flood and erosion prone land
- Promote sustainable development of the wider catchment

- Use planning and community preparedness to ensure sustainable land use
- Identify options to manage the flood risk

Te Kāuru - Upper Ruamāhanga Floodplain Management Plan

Te Kāuru is being developed as a long-term approach to floodplain management within the Upper Ruamāhanga River to the Waiohine confluence, and includes the Waipoua, Waingawa, Kopuranga, Whangaehu, and Taueru rivers from their headwaters within the Tararua Ranges and Eastern Hills to their confluences with the Ruamahanga River. The catchment has a total area of approximately 1,560km.

The FMP incorporates environmental, cultural, and recreational values the community holds in relation to the catchment, and how floodplain management can seek to maintain or improve these values.

There are five main aims for the Te Kāuru Floodplain Management:

1. To work together to develop a sustainable floodplain management plan.
2. To support sustainable economic development
3. To protect and improve the cultural values of rivers
4. To recognize local community needs and build resilient communities
5. To protect and enhance our natural spaces.

Current river management approach

The current river management approach is to keep the rivers within their inner management line (Figure 1). When a river erodes into the buffer, river management works are undertaken to shift the river back into the inner management line as soon as is practicable. These river management works often consist of machinery in the river channel.

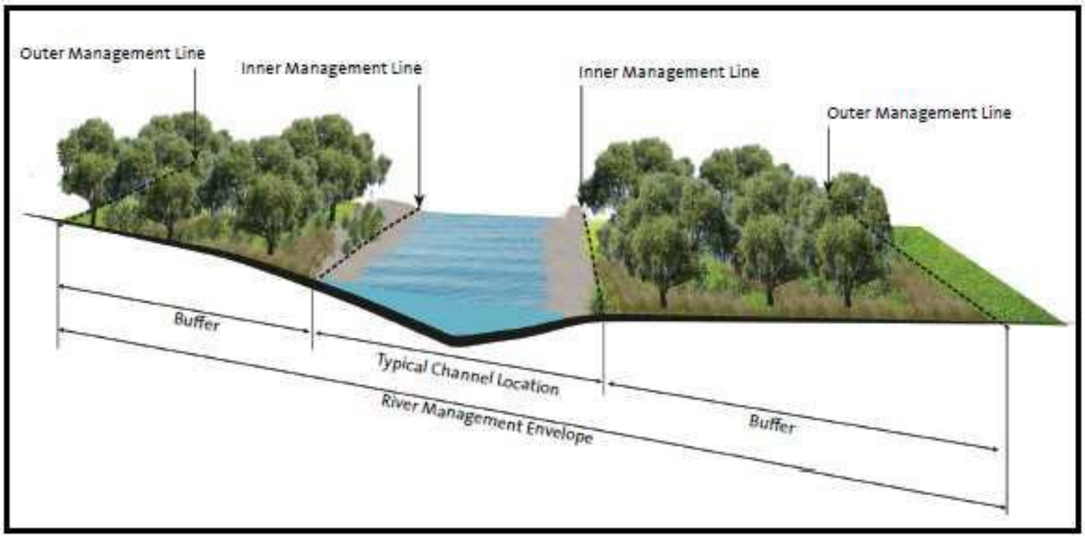

Figure 1: River management envelope

The draft Te Kāuru Upper Ruamahanga FMP proposes to give the rivers more room. This will mean that the rivers would be allowed to move within the buffer area and consideration will be made whether land outside the buffer is at risk prior to undertaking river management works to shift the river back to the inner management line.

The intent of allowing the rivers more room is to give them more space to carry out their natural processes.

This shift in approach will mean there will be less frequent intervention, meaning machinery will be in the river less often. However, more large interventions may be required as a result.

Buffers

Buffers are an envelope of land beyond the river channel that are maintained as areas for erosion control and for protection.

 

In the Wairarapa, the planting of willow trees within buffers for river and erosion management has been a practice for more than 30 years. Greater Wellington believe that vegetated buffers have assisted to reduce erosion and sedimentation as well as providing cover and habitat for wildlife. GW also believe that nutrient and pathogen runoff has also been reduced as a result of the vegetated buffers. However, further investigations are needed to confirm if this is in fact the case or even likely.

A significant portion of buffers are currently not planted and in some cases landowners are grazing their livestock up to the river's edge. Some buffer areas have high banks and erodible cliffs. These areas will not be able to be planted as their root zone will be too high above the river to have any effect on slowing erosion. In this instance, the FMP proposes to allow partial or full erosion of the cliff so that a vegetated buffer can be established at river level.

Within Te Kāuru planting is proposed for all buffers where appropriate. Planting is proposed to consist of hybrid willows along the front edge of the buffer, as these are fast growing robust trees and dense root mass that binds the bank edge soils together. A selection of natives are proposed behind the willows to improve biodiversity, enhance visual amenity, improve water quality and further stabilising stream and river beds. Different plant types could also be explored that may create a benefit for the adjacent landowners by providing some form of fodder for stock (once harvested from the buffer – cut and carry), nutrient uptake or honey production.

DairyNZ are currently undertaking research along with NIWA looking at options for farmers with regards to riparian planting that will benefit the environment but at the same time

produce fodder for stock, food for people or even pharmaceuticals.
https://www.dairynz.co.nz/news/latest- news/research-into-productive-riparian-buffers/////

The river management design lines are in place throughout the western rivers: Ruamahanga, Waingawa and Waipoua. There are no design lines on the eastern rivers: Kopuaranga, Taueru and Whangaehu. Vegetated buffers are not proposed on these rivers, but riparian planting may still be appropriate.

The buffer areas in the western rivers vary in width. To view the buffer lines please refer to the GIS mapping on www.tekauru.co.nz.

River dynamics

The upper Wairarapa valley rivers are connected and therefore when there is a rainfall event it will generally affect all of the rivers. The western rivers are gravel based, wide rivers, whereas the eastern rivers are narrow soft, silt based. Below is a brief summary of each rivers characteristics.

Western rivers:

Ruamahanga River

The Ruamahanga River is well known for its flood events.

The bed of the river had previously been badly choked by willows, restricting flood flows, and the channel was of inadequate size for the floodwater volumes and of irregular alignment.

Various river management schemes were subsequently implemented to provide river alignment stabilisation, bank edge protection, and improved stopbanks to reduce the incidence of flooding to adjacent floodplain along many sections of the river.

Waingawa River

The Waingawa River is very steep and powerful, and exists in an entrenched fairly tight, naturally confined floodplain.

Flooding risk from the Waingawa is limited due to its entrenched form, but erosion is significant. Due to steepness the river runs fast and during a flood event will reshape its channel.

Waipoua River

The Waipoua River is a potential flood risk to Masterton.

The flood risk from the Waipoua can be compounded by the backwater effects of flooding in the Ruamahanga River. Due to this the Waipoua was substantially modified and straightened in the 1930s and 1940s along with establishment of stopbanks.

Eastern rivers:

The Kopuaranga, Taueru and Whangaehu Rivers have all experienced significant flood

events.

During the 1960s and 1970s crack willow was planted to manage flood hazards. However, these willows eventually led to significant erosion and chocking of the river channel. In some instances the river channels migrated to adjoining areas and as a result caused an increase in sedimentation which in turn further constricted the channel.

Specific Questions

1. How does the river benefit from more room?

a. Natural Character

Natural character is the natural condition of the river before any modification has occurred.

Natural character is referenced within section 6 of the Resource Management Act. Section 6 (a) states '*In achieving the purpose of this Act, all persons exercising functions and powers under it, in relation to managing the use, development, and protection of natural and physical resources, shall recognise and provide for the following matters of national importance…the preservation of the natural character of the coastal environment (including the coastal marine area), wetlands, and lakes and rivers and their margins, and the protection of them from inappropriate subdivision, use, and development'.*

Natural Character (NC) is not natural state or naturalness (Figure 2) but rather "*is that dimension of its character which is an expression of nature, and also may include anthropogenic values including cultural, aesthetic etc.*", and includes the extent to which natural elements, patterns and processes occur. This distinction may seem rather arbitrary, but can be extremely important. If you define natural character as naturalness people automatically decide that modified systems have limited or no natural character, and so potentially have reduced value and or limited opportunity for restoration or enhancement, unless you put the catchment back into native forest, or similar that was present in the 1800s (which also may be short sighted temporally)? If the term natural character is defined as meaning naturalness, this limits the meaning of Natural Character in the RMA. When you define natural character as "*that dimension of its character which is an expression of nature*", then you find you can have natural character in modified systems, and that you can maintain Natural Character in managed systems e.g. it can be used as a tool to inform better river management practices and protect ecological integrity.

This definition is more in line with decisions from the Environment Court law. The ecological description of natural character was identified and protected in the *Ministry of Works and Development v Marlborough Sounds Planning Authority* judgment where ecological processes were considered as being part of the area's natural character. However, judicial protection has not just extended to natural character of unmodified landscapes. In the *Southland Airport* case the character of the modified or cultural landscape was deemed to have value and deserve protection, and the judge declined the application in favor of the appellant's amenity and enjoyment values including tranquility. In *Brook Weatherwell Johnson v Tasman District Council* the judge ruled that a modified hill overlooking Motupipi estuary had natural character worthy of protection.

Rivers are not static systems they are dynamic, changing temporally and spatially, in response to changes in catchment and climatic characteristics, as such the components of natural character change. Each river comprises a unique assemblage of morphological components (bars, riffles, pools, runs), reflecting the unique flow regime conditioned by runoff from the catchment; unique sediment supply, both in terms of volume and calibre (size); and unique channel boundary conditions, notably bank composition and channel gradient. The precise morphology and character of a reach reflects the unique combination of these variables. River channels which have adjusted to an equilibrium form within their framework of sediment and flow regime within the boundary conditions of a catchment should not be considered to be absolutely stable. Stability is relative and natural systems are dynamic, responding to discrete flood events in particular. Well-adjusted river systems are best understood as operating within a dynamic equilibrium. River morphology adjusts to subtle changes in flow and sediment supplied to the system from the catchment. Whilst boundary conditions (gradient and bank composition) could be considered as being relatively constant, discharge and sediment supplied to a river is highly variable, responding to discrete natural events (e.g. storms, landslides). Rivers are therefore naturally dynamic and responsive systems, adjusting their form in response to changes in key channel forming variables on an event basis. The natural character of rivers is dynamic.

Gary Williams writes that *"the natural character of a river reach, in its physical expression,* *depends on the intensity of the flow forces, the supply of sediments to the reach, and the resistance of the channel bed and banks. It is more a matter of the processes at work than a specific state of channel condition. The channel dynamic and form will be different, but the difference will be the same as occurs along rivers naturally, as the formative influences change in strength or intensity*". That is catchments vary throughout New Zealand, and over time, and rivers adjust to maintain a state of dynamic stability for example a river which was once glacial and then becomes temperate forested and free flowing over time has the same degree of natural character, even if its characteristics have altered. Likewise human modification may change a rivers natural character by managing the river channel but this does not necessarily mean that the river has lost all natural character if the river maintains its dynamic state and its processes continue to support ecological integrity.

Figure 2. Illustrative examples of rivers with high (left) and low (right) natural character.

Where the equilibrium form of the river is wider, giving more room for the river allows for the natural equilibrium channel to develop (Biron *et al.*, 2014; Buffin-Belanger *et al.*, 2015; Fuller & Death, 2018; Fuller & Death, in press). River corridors that are over-narrow restrict development of these natural equilibrium forms and the resulting river morphology will reduce diversity. This requires a spiraling need for more and more engineering to force the river into its “preferred” channel (Biron *et al.*, 2014). In the worst case scenario the river may even avulse from the original channel. When the channel is constrained sediment builds up aggrading the river up to, and potentially over stopbanks (Sinha, 2009). This may have catastrophic effects on human life and property. The Kosi River in eastern India avulsed in August 2008 killing up to 150 people and displacing a further 30 million (Sinha, 2009). Engineered avulsions in the Yellow River, China, in 1931 are believed to have killed up to 3 million people (Zhuang & Kidder, 2014).

The equilibrium form of the river adjusts to catchment boundary conditions (slope, geology, climate, vegetation, sediment supply, discharge), where these conditions change, or are changed, e.g. by forest clearance, the natural form of the river adjusts to the new variables and the channel changes in response. Geomorphological effects of future climate on rivers remain difficult to ascertain (Kiss & Blanka, 2012), but it seems clear that sediment transport dynamics will be altered (Radoane *et al.*, 2013). Where discharge and sediment supply increases, as is the case in response to land clearance, the river channel will naturally widen; trying to maintain a narrowed corridor works against these processes and reduces the diversity in morphology that natural processes would tend to develop.

Allowing river processes to occur over a greater width effectively provides greater potential for natural ecogeomorphic processes (= natural character). (Biron *et al.*, 2014) found that a minimum space of approximately 1.7 times the channel width was appropriate for accommodating smaller floods in three Canadian rivers but wider channels were needed for larger floods. This potentially allows reestablishment of vegetated boundaries (as would have existed prior to European colonization) in a manner that is currently being suppressed by recurrent spraying and removal of woody vegetation from bars and floodplains.

River banks are often protected with concrete and channels straightened, decreasing complexity in geomorphic structure, with limited consideration of the interactions between channel morphology and sediment transfer (Darby & Thorne, 1995; Fuller *et al.*, 2011).

Where the natural behaviour of the reach or system being managed is not properly understood, engineering failure may occur as the river channel adjusts to remove or work around its imposed engineered 'straightjacket'. Hardening banks and constraining what would otherwise be laterally active channels, tends to result in bed scour. This results from excess stream power and deepens the channel. The process is self-perpetuating as the channel deepens, flows become further confined within-channel and armoured banks, further increasing scour. In containing larger floods and concentrating flows, entrenched channels generate higher transport capacities, resulting in the mobilisation of large volumes of bedload and further bed degradation (Fryirs & Brierley, 2001).

Such degradation is commonly observed in laterally constrained rivers (Gilvear & Winterbottom, 1992; Wishart, Warburton & Bracken, 2008) and these types of channels are frequently engineered, which further reduces geomorphic diversity. In the Rangitikei River in New Zealand, channel straightening to protect urban areas and bridges has channelized a formerly braided river (Fuller *et al.*, 2012), which is now undermining the banks as the channel degrades requiring further engineering works. Engineered reaches thus remain unstable, often with different dimensions from their natural counterparts.

Allowing the river channel to adopt a more natural form will probably result in the river adjusting considerably over the short term. However, in the longer term, it will allow for more sediment transport and less risk of high flows breaching the wider river corridor into people's houses and farms. The more natural the channel flood plain the less the avulsion risk and the greater the potential for the river to look after itself. The changes could be monitored with drone mapping, cross-section profiling and/or measuring the Habitat Quality Index (HQI) at key locations (Death, Fuller & Death, in prep).

b. Aquatic life

The importance of both instream and flood-plain habitat in affecting riverine biological communities has always been widely understood, and integral to interpreting most stream ecology research (Hynes, 1970; Hynes, 1975). The river ecosystem does not end at the water's edge but is intimately linked to the wider flood plain. The influence of the channel shape in determining river ecosystem structure and function often forms the underlying framework for many hypotheses in stream ecology such as the River Continuum Concept (Vannote *et al.*, 1980), Network Dynamics Hypothesis (Benda *et al.*, 2004) and the Riverine

Ecosystem Synthesis (Thorp, Thoms & Delong, 2006; Thorp, Thoms & Delong, 2008). At the individual species level the habitat and geomorphological requirements of salmonids have probably received the most attention (e.g., (Kondolf, 2000; Fukushima, 2001; Sear & DeVries, 2008; Wheaton *et al.*, 2010). However, the habitat requirements for other freshwater fish and invertebrates have also received considerable attention highlighting their critical importance (Death, 2000; Helfman, 2007; Barnes, Vaughan & Ormerod, 2013; Gorski *et al.*, 2013; Koehn & Kennard, 2013). Although different species and/or life stages have particular habitat requirements the more diverse and natural the river channel the healthier and more natural the biological community.

The link between geomorphological changes in river morphology and how they impact on the associated river biota has been widely considered in the literature (Newson & Newson, 2000; Stallins, 2006; Vaughan *et al.*, 2009; Brierley *et al.*, 2010; Darby, 2010; Poole, 2010; Rice, Lancaster & Kemp, 2010). If river morphology is altered then so too is the habitat for the animals and plants living within that river. Although there are surprisingly few studies that specifically quantify the linkages between river morphology and the organisms that inhabit those rivers (Vaughan & Ormerod, 2010; Gorski *et al.*, 2013; Gostner *et al.*, 2013). (Elosegi, Díez & Mutz, 2010; Elosegi & Sabater, 2013) in their review of the effects of human modification of riverine geomorphological character on biodiversity and ecosystem function concluded this lack of research was a result of the highly variable nature of geomorphology depending on climate, geology, catchment position, land use and flow regulation.

Floods are critical structuring forces for stream invertebrate populations and communities (Resh *et al.*, 1988; Lake, 2000; Death, 2008). This has even led a number of ecologists to advocate the return of natural flood regimes (the natural flow paradigm) to regulated rivers as one mechanism for maintaining the ecological integrity of downstream reaches (Poff *et al.*, 1997). However, floods are projected to increase in size and frequency (Death, Fuller & Macklin, 2015). The effects of these larger floods on riverine biological communities will be exacerbated by river engineering to protect the increasing threat to human life and infrastructure (Wilby, Beven & Reynard, 2008; Jongman *et al.*, 2014). River management for flood protection has tended to focus on maintaining a 'stable' channel form to maximize flood conveyance, which has not usually benefited biota (Darby & Thorne, 1995; Harvey & Wallerstein, 2009). There are few species that occupy the fast deep channels created by such engineering. River banks are often protected with concrete and channels straightened, with geomorphic diversity and complexity removed (Darby & Thorne, 1995; Fuller *et al.*, 2011). Undercut banks, instream wood and overhanging vegetation are removed to facilitate the rapid removal of water during floods. These all provide habitats for a wide range of biota permanently or during floods. Native galaxiid fish in New Zealand repeatedly seek refuge under particular large boulders during floods despite spending the rest of their time some distance away along the stream reach (McEwan & Joy, 2013). Some fish move away from the main channel and some invertebrates may similarly be capable of sensing substratum movement and escape to side channels to avoid being washed away (Gibbins *et al.*, 2005; Death, 2008; McEwan & Joy, 2013). However, if channelization and/or fragmentation have removed their escape routes, survival may be impossible.

Riparian areas are also critical habitat for many species and the exposed dry area of river beds created by floods are used by a wide range of birds, reptiles, plants and invertebrates (Baxter, Fausch & Saunders, 2005; Keedwell, 2005; Steward *et al.*, 2011).

(Buffin-Belanger *et al.*, 2015) calculated the economic value of ecosystem services provided by riparian wetlands and increased buffer zones within a wider flood plain of three Canadian rivers. They found enhanced value ranging fromCDN$0.7 to $3.7 million for the three rivers, with ratios of benefits over costs ranging between 1.5:1 and 4.8:1 over a 50-year period.

c.   Water quality

Although many perceive channelized floodways as a rapid vehicle for removing nutrients and other chemical contaminates. These chemicals inevitably end up in the coastal marine ecosystems where they can have an equally detrimental impact. If the river is provided with a more natural flood plain this can benefit water quality by allowing for great denitrification. Historically wetlands and flood plains would serve as areas where water ponded and allowed bacterial communities to denitrify many of the nutrients from the water column (Hill, Vidon & Langat, 2004; Greenwood *et al.*, 2012). In fact, artificial flood plains, termed two-stage ditches, are being adopted in agricultural streams as a mitigation strategy to reduce nutrients (Davis *et al.*, 2015; Mahl *et al.*, 2015; Roley *et al.*, 2016; Faust *et al.*, 2017).

In mid- to downstream reaches, there is some potential for increases in floodplain vegetation to attenuate pollutants e.g., Manuka is believed to filter nitrogen. The greatest effect would however be where adopted width increases result in channel dynamics (i.e. periodic abandonment) that produce off-channel wetlands which could provide filtration benefits along the margins.

Deposited and suspended sediment is the other major potential contributor to declines in water quality. The effect of channel widening on sediment transport (see above) is complex. There will clearly be some increases as the channel adapts and accommodates to the new morphology, however increased sediment transport is an unavoidable consequence of anthropogenic changes in land use. If the channel is too constrained this sediment will aggrade and potentially result in channel avulsion, or at least require expensive human intervention to prevent it. Increased deposited and suspended sediment is not ideal but allowing a greater diversity and complexity in the channel form will hopefully allow for areas of both scouring and deposition more characteristic of a natural river. In turn these sediment dynamics are what most of the highly mobile river biota are used to and will allow them to respond as they have been for millennia.

d. Water quantity

In general water quantity is unlikely to be affected by giving the river more room, although it is possible that in its widened corridor, flow is distributed across multiple channels, with some channels being of an ephemeral nature

The collective increase in floodplain roughness (e.g. from vegetation) as well as channel form -roughness (e.g. from increased hydraulic complexity) might be expected to increase downstream lag times. This has some potential to attenuate flow peaks, but to what degree is unknown. If the creation or linkage with wetlands is included this attenuation ability could be greatly increased.

e. Cultural values

Allowing the river more room re-connects the river with its corridor and adjacent floodplain. This may have significant cultural value, since iwi value the catchment as a whole and with its parts functioning connections (slopes-channels-floodplains).

Potentially, greater opportunities for edible and medicinal plants to become established and persist. Increased potential for off-channel, secondary channel, and/or wetland habitats to form and persist (e.g. that would benefit eels).

2. How does the river benefit from a planted riparian buffer?

Introduction

Riparian strips are vegetated areas that extend along streams, usually forested, which help shade and partially protect the waterway from the impact of adjacent land uses. The riparian zone forms a natural buffer between the surrounding land and waterways. The protection and management of the riparian zone may have important implications for channel form, water quality and biodiversity (Renouf & Harding, 2015). Riparian zones are the interface between the aquatic and the terrestrial ecosystems which connect and affect the ecological functions of both systems (Gregory *et al.*, 1991; Naiman & Decamps, 1997; Naiman, Decamps & McClain, 2005). Riparian zones contribute with valuable biodiversity and ecosystem services, which are important for regulating flow and nutrient transport in waterways. Riparian buffer strips play a key role in improving water quality in associated waterways, and are widely promoted as a “best management practice” by agricultural agencies, environmental groups and regional councils.

What are riparian buffer strips?

Riparian buffer strips (RBS) encompass the vegetated strips of land that extends along streams and rivers (Quinn, Cooper & Williamson, 1993; Martin *et al.*, 1999). This can range from a single strip of vegetation (grass filter strips) from which livestock or other agricultural activities are excluded, to a completely vegetated native forest riparian strip (Parkyn, 2004) (Figure 3.).

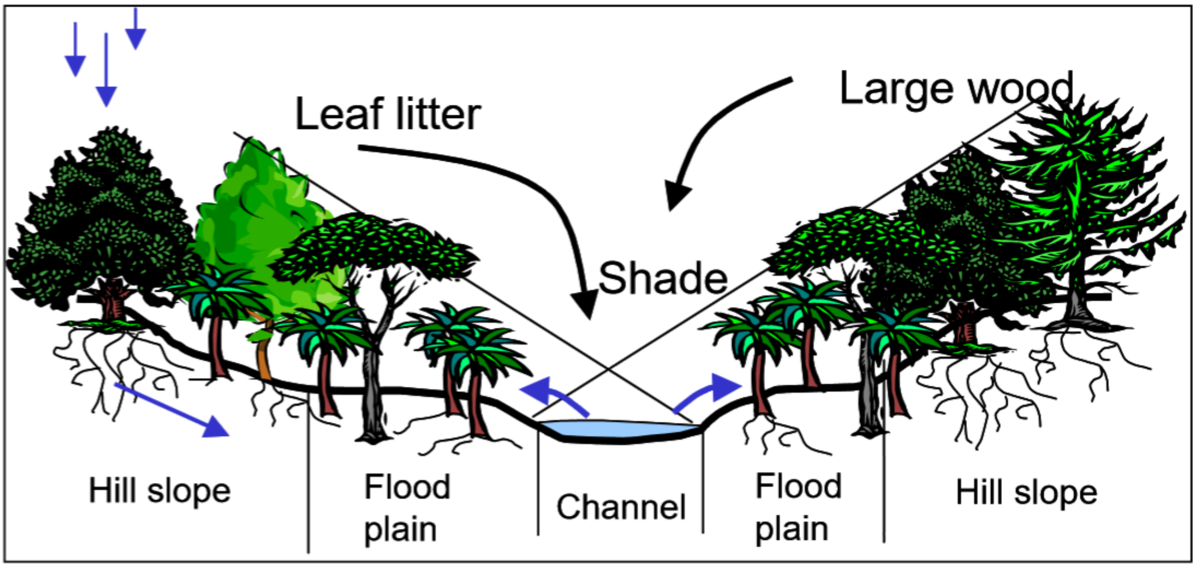

Figure 3 The riparian zone is the land beside the stream that interacts with runoff from hillslopes and stream water when this overflows into the floodplain.

Riparian functions

Riparian buffer zones are often advocated as environmental management tools for reducing impacts of land use activities on water quality (Parkyn *et al.*, 2003; Parkyn, 2004; Yuan, Bingner & Locke, 2009a; Weller, Baker & Jordan, 2011). As the interface between terrestrial and aquatic environments, they have an extremely large influence on stream water quality relative to stream size (Quinn, Suren & Meurk, 2003; Boothroyd *et al.*, 2004; Harding, 2009). Importantly, they sustain water quality by sequestering nutrients and faecal contaminants (Fennessy & Cronk, 1997; Quinn, Suren & Meurk, 2003; Collins *et al.*, 2004; Parkyn, 2004; Aye *et al.*, 2006; Collins *et al.*, 2007; Yuan, Bingner & Locke, 2009a; Weller, Baker & Jordan, 2011; Roberts, Stutter & Haygarth, 2012), regulate instream and forest temperature (Collier *et al.*, 1995; Davies-Colley, Payne & Van Elswijk, 2000; Meleason & Quinn, 2004; DeWalle, 2010), limit soil erosion (Weller, Correll & Jordan, 1994; Abu-Zreig, Rudra & Whiteley, 2001; Gharabaghi *et al.*, 2002; Mankin *et al.*, 2007; Helmers *et al.*, 2012; Mayer *et al.*, 2014; Sweeney & Newbold, 2014a) and maintain instream biodiversity (Barling & Moore, 1994; Collier *et al.*, 1995; Davies-Colley, Payne & Van Elswijk, 2000; Corbacho, Sánchez & Costillo, 2003; Parkyn *et al.*, 2003; Boothroyd *et al.*, 2004; Meleason & Quinn, 2004; Parkyn, 2004).

An understanding of how riparian zones function is very important when designing riparian management strategies. Riparian functions are expanded on in Table 1

Key Riparian Functions	Explanatory notes
Geomorphic and hydraulic characteristics	
Stream bank stability	The root systems of trees and grasses strengthen streambanks, whilst groundcover reduces surface erosion and undercutting
Downstream flood control	Well-developed riparian zones increase the roughness of stream margins, slowing down flood flows; reducing peak flows downstream
Habitats	
Habitats for aquatic invertebrates	Well-developed riparian zones provide suitable habitats and food sources for both the adult (terrestrial) and juvenile (in-stream) phases of stream insects
Instream habitats for native fish and trout	The overhanging branches, tree roots and woody debris enhance habitat diversity and create spawning grounds for native fish (such as Inanga), trout and crayfish
Links riparian and terrestrial vegetation	Riparian zones provide ecological corridors for birds and terrestrial wildlife, although the spread of weed species can also be facilitated this way
Improves aesthetic and landscape values	Provides recreational opportunities and values
Water quality and habitat characteristics	
Shade for stream temperature	Riparian buffer zones maintain lower summer maximum temperatures. Removal of shade can result in summer temperatures that can be lethal to some invertebrates (most invertebrates have an upper threshold for survival which can be comparatively low e.g. 19C for stoneflies), or winter temperatures that are too warm for successful trout fishing

Shade for periphyton control	High light levels can exacerbate periphyton growth, leading to increases in instream primary production, reduced DO, and changes the invertebrate community composition
Woody debris and leaf litter input	Riparian trees supply food to stream invertebrates and fish in the form of leaf litter, insects and microorganisms
Improves fish passage	Overhanging vegetation protects migrating fish from predators and light
Contaminant buffer	
Filtering surface flow	Grassy vegetation reduces the velocity of surface flow, enhancing settling and infiltration of particles. Filtering and nutrient uptake by plants and microbes follows
Plant nutrient uptake from groundwater	The roots of riparian plants intercept groundwater, reducing nutrient input to streams
Denitrification N control	Denitrifying bacteria in riparian soils can remove substantial quantities of dissolved nitrate from groundwater, expelling this to the atmosphere as nitrogen gases
Control of direct animal waste input	Preventing direct access of stock to waterways prevents compaction and erosion damage to streambanks, as well as direct input of nutrients and faecal pathogens in the form of dung and urine

a. Natural character

Vegetation is an essential element of the river's "natural character". Increased lateral channel migration may be expected during an initial transition period, meaning plant stock installed by humans will need to be overplanted. Depending on the river and reach in question, it is possible that recovery of more stable channel forms may not occur without supplemental treatments. Such treatments would need to increase local resistance to facilitate more stable non-channel units where vegetation will be able to establish and persist. An initial wait-and-see period would be appropriate, but, again depends on the reach in question.

The natural character of the river will be improved where the river corridor is (a) widened and (b) has a buffer planted with native vegetation. But planting should not proceed until an equilibrium width has been attained or determined, because the river will widen via bank erosion, thus removing any plantings in this zone. Once a suitable width has been attained, planting of the buffer will provide a potential wood source for recruitment, which will add diversity to the river morphology and form. Some erosion of this buffer should be expected.

b. Aquatic life

As with the expansion of the river corridor, riparian zones increase habitat diversity and connectivity with other habitats. The greatest improvements in habitat diversity are likely to occur when riparian management involves planted trees or remnant forest rather than simply a grass strip (Parkyn & Smith, 2011).

The principal effect of the riparian buffer is to act as a barrier to nutrients, sediment, pathogens and other potential contaminants running off the land and to prevent it entering the waterway (see below). It will also stabilise stream banks and limit erosion and undercutting. The reduced inputs of fine suspended sediment following bank stabilisation may also improve conditions for migrating fish such as the banded kokopu, whose juvenile migrations are adversely affected when turbidity increases (Death & Joy, 2015; Holmes *et al.*, 2016). The vegetation can also take up some of the nutrients. If a forested riparian zone exists this can also serve to limit light reaching the stream bed, preventing excessive periphyton growth. Water temperatures may also be are reduced if sufficient lengths of upstream shade exist, leading to improvements in invertebrate communities (Parkyn & Smith, 2011; Feld *et al.*, 2018). This can be important as many New Zealand stream invertebrates such as mayflies and stoneflies, are sensitive to water temperatures over 20°C, temperatures which are often exceeded in open pastures (Quinn *et al.*, 1994).

The riparian buffer zone can also provide suitable habitat for the adult stages of many aquatic invertebrates (the in water life stage of many aquatic animals is the juvenile form with winged adults emerging from the water to mate and reproduce) (Collier & Scarsbrook, 2000; Collier & Winterbourn, 2000; Smith et al., 2002; Smith & Collier, 2005). Furthermore, the air temperatures and humidity are lowered with riparian plantings, and wind exposure is reduced in the riparian zone where some invertebrates spend the adult stage of their lives and some native fish such as the banded kokopu and short-jawed kokopu lay their eggs (Collier & Smith, 2000; Davies-Colley, Payne & Van Elswijk, 2000). Terrestrial insects and mammals from riparian zones often form a major component of the diet for many native and sport fish at certain times of the year (Main, 1988; McDowall, 1990).

Riparian buffer zones, particularly those with forested vegetation, are also important for providing instream habitat for native fish and trout by enhancing habitat diversity (e.g., overhanging branches, bank under cutting), creating pools and areas of day time and flood refuge. Grassy or forested river banks also provide spawning habitat for Inanga and other Galaxias species, respectively.

Riparian planting influences instream biodiversity by providing woody debris as tress fall into streams, providing habitat diversity and cover for aquatic invertebrates, fish and freshwater crayfish (Martin *et al.*, 1999; Parkyn *et al.*, 2003; Parkyn, 2004; Hawes & Smith, 2005; Sweeney & Newbold, 2014a). Riparian plantings also increase the shade and food sources (such as leaves) (Collier & Smith, 2000).

Thus riparian buffer zones also serve to maintain the proper ecological functioning of instream ecosystems.

c. Water quality

One of the most important functions of riparian buffers is enhanced infiltration of surface runoff (Abu-Zreig, Rudra & Whiteley, 2001; Gharabaghi *et al.*, 2002; Hawes & Smith, 2005; Mankin *et al.*, 2007; Collins *et al.*, 2011; Helmers *et al.*, 2012; Sweeney & Newbold, 2014a). Buffer zones, particularly grass filter strips, can reduce diffuse pollutant transport by providing flow resistance which reduces the flow velocity and thus the sediment transport capacity of surface runoff. This leads to enhanced deposition of sediment and sediment associated pollutants (particulate P and N). These slower flows also regulate the volume of water entering rivers and streams, thereby minimizing flood events and scouring of the streambed (Hawes & Smith, 2005).

Increased infiltration can occur in buffer zones due to the change in soil structure associated with the change in vegetation type. If stock is excluded from the zone, infiltration capacity is also increased due to lack of compaction by trampling (Collier *et al.*, 1995).

There are several mechanisms for the removal of soluble nutrients – largely N - from subsurface flow. Chemical processes such as denitrification remove dissolved nitrates in the form of N gases, a process that is particularly effective in carbon rich soils, such as in riparian zones (Weller, Correll & Jordan, 1994; Neilen *et al.*, 2017). Plant uptake also removes soluble nutrients, and eventually returns nitrogen to the system as the plants die and decompose (Weller, Correll & Jordan, 1994). Furthermore, the longer the effluent resides in the soil's active root zone, the greater the opportunity for microbial bacteria to die off (Houlbrooke *et al.*, 2004; Collins *et al.*, 2010).

There is an issue with microbe and nutrient removal from subsurface flow in agricultural systems however. Subsurface artificial drains often underlie dairy pastures where soils have poor natural drainage. Although these drains effectively reduce soil saturation and the generation of surface runoff, they also rapidly transport both microbes and nutrients straight to the waterways, bypassing the riparian zone and any chance for uptake (Hawes & Smith, 2005; Collins *et al.*, 2007). In addition, on soils with a high degree of preferential flow (water flows through soil cracks, large pores and worm channels rather than through the fine pores of the soil matrix), soil-water contact is minimal (Collins *et al.*, 2007). This provides little opportunity for the filtration of adsorption of microbes or nutrients. Pollutants can therefore be easily transported to subsurface drains (and subsequently waterways or groundwater) (Collins *et al.*, 2007).

d. Cultural values

As above, a planted riparian buffer, particularly one with native vegetation will make for a healthier awa that is valued by most Tangata whenua. A healthier river can also provide for more abundant and healthier mahinga kai (Death *et al.*, 2017b) provided that access to that kai is not limited by engineering and planting works.

e. Help stabilize the buffers and assist with maintenance

A widened channel with more room to move would be expected to put less pressure on banks, so the buffer zones are likely to be retained, if the equilibrium channel develops. However, there will always be a tendency for lateral shift. It should be easier to keep the river with a much wider corridor than it is a narrow one.

Without resistant elements (e.g. mature vegetation or wood jams), it is possible that localized aggradation may occur at some reaches/sub-reaches if sufficient depth does not develop to maintain sediment transport. This is a potential risk in transitioning management schemes. It may thus still be necessary for some intervention (e.g. gravel extraction) if this occurs to prevent avulsion. There is the potential with this of a premature declaration that a room-to-move approach is too risky as the river adjusts to its new morphology.

f. Opportunities for riparian plants to be used for food, stock food and pharmaceuticals.

Many native riparian plants have been used historically for cooking (e.g., Horopito, kawakawa), textiles (flax) and traditional medicine (e.g. kawakawa). Furthermore, many of these same plants are being utilised more and more in modern commercialised ventures (e.g. Manuka honey). Judicious planting and maintenance of diversity may provide additional returns over and above those of river management.

3. How could we assess effectiveness of the room-to-move management

Giving the river more room has the potential to become the template for future management of rivers. So I would recommend expending some time and effort in assessing how effective the strategy is, to investigate not only its potential in the Ruahmahanga, but also the potential benefits for other rivers in the region. From this perspective it might be useful for the Innovative River Solutions team at Massey to become more directly involved. Irrespective of whether funding is available for student research we could develop potential graduate and undergraduate studies around what is in essence a large experiment. In fact it would also be very interesting to also incorporate the social and cultural aspects of the project with other areas of expertise at Massey that we work with.

The challenge is that allowing the river channel to adopt a more natural form will probably result in the river adjusting considerably over the short term. But, in the longer term, it will allow for more sediment transport and less risk of high flows breaching the wider river corridor into people's houses and farms. The more natural the channel flood plain the less the avulsion risk and the greater the potential for the river to look after itself.

It would be sensible to measure channel morphology over time, perhaps using drone or aerial photography and to report those changes using the Habitat Quality Index (HQI) (Death, Fuller & Death, in prep). Other potential monitoring could include river cross-sections, depth distributions, bank vegetation canopy and the caliber of floodplain trees.

Assessing the biological response to giving the river more room will also be very challenging. Many other factors, such has high nutrient levels, are likely to be having an equally powerful effect on the river biota. Although fish are the organisms most likely to benefit directly from the morphological changes, however, they are also the organisms most limited by other activities in the catchment such as access (Death *et al.*, 2017a). Again the native fish HQI might be the best way to assess the potential improvements in fish habitat. Invertebrates are probably less likely to respond as directly to habitat changes but are considerably easier to measure and link with local changes in the environment. So while I do not recommend reporting the usual water quality biological metrics from invertebrate monitoring (e.g. MCI, QMCI) reporting invertebrate indicators such as EPT and geomorphological indicator species (e.g., elmid beetle larvae that we are developing at Massey). Monitoring once a year at key locations should be more than adequate.

An assessment of cultural health by the local Tangata whenua would also be very useful and may assist with them being incorporated into the project as real partners.

4. What would be the perceived risks of the proposal to plant the buffers? How might we quantify these risks?

As mentioned earlier there will be considerable adjustment to the river morphology as the channel moves from a more constrained position to one with more room. Clearly this will depend on an array of complex reach specific criteria e.g. how constrained the current channel is, how much more room is provided for the river, current sediment levels and supply. There is definitely the potential that increased roughness, sediment migration and channel realignment may cause unexpected deform of active channels and potentially overtopping or avulsion. Buffers may also be eroded with lateral channel shift. The balance between giving the river more room for its natural hydromorphology and the constraints of current infrastructure and channel form will be difficult, hence the adaptive monitoring mentioned above. An assessment of current floodplain morphology and the proposed "new" river form is probably best assessed with channel and river corridor surveys using LiDAR and/or drones. This could potentially be worked into a risk assessment map of flood potential.

5. If we allow the river to erode into the buffers and then undertake larger scale river works, will this have more of an effect than if we did smaller river works more often?

This is an extremely difficult question to answer. Clearly more works will be required as the channel adjusts to its new form. Ideally, the wider the corridor the less the need for intervention, so smaller works could be used to keep the river in this widened form. However, this will again depend on the specific reaches. Is the river allowed the full channel capacity or is it simply a little more room? Careful planning mentioned above and monitoring of how the channel adjusts will be needed, at least initially.

Rapid colonization of exposed gravel by weeds may result in a re-narrowing of the active channel, which heightens the risk of unpredictable channel switching / avulsion within the corridor. Clearing of weeds in the widened channel corridor will still be required, to maintain a mobile channel and bar configuration.

From the perspective of the river biota smaller more frequent intervention is probably preferable (although there is no research on this to the best of my knowledge). The organisms are well adapted to severe disturbances from floods (Death, 2008) and provided they have suitable upstream colonization pathways they should recover relatively quickly to disturbance of smaller river reaches (Death & Death, 2014).

6. How will giving the river more room impact on sediment supply from potential bank erosion?

This question implies that room-to-move will result in more bank erosion than presently occurs. This seems unlikely. There are many places where there are already accelerated rates of bank erosion from current regime that strips vegetation. In my view, the primary benefit of room-to-move is having a wider corridor where natural resisting elements (bar forms, bed armor, and vegetation) are allowed to exist while still accommodating current design floods. Once those stabilizing elements are in-place, erosion rates are likely to decrease from those at present. As noted above, the critical consideration is the transition period and recognition that not all reaches will respond the same way. Any potential short term increase in sediment will hopefully be nullified by the longer term decreases.

7. **Does the width of the buffer area dictate the overall benefits? For example, a wider buffer is more beneficial than a narrow buffer?**

The width of a buffer will determine its benefit (Parkyn, Shaw & Eades, 2000; Hickey & Doran, 2004; Lee, Smyth & Boutin, 2004; Yuan, Bingner & Locke, 2009b; Shan *et al.*, 2014; Sweeney & Newbold, 2014b). In general the wider the buffer the greater the range and quantile of benefit. Several studies have shown that efficient buffer widths can range from 5 m for bank stabilization and stream shading, to 20 m for self-sustaining buffers, to over 50 m for biodiversity gains. Several meta-analyses have indicated that 30 m buffer strips are needed to protect stream health (Zhang *et al.*, 2010; Sweeney & Newbold, 2014a), while others have recommended a 50 m buffer strip (Mayer *et al.*, 2007). Although overall benefit increases, the rate of increase declines as width increases (Yuan, Bingner & Locke, 2009b). Ultimately, the width of a riparian buffer depends on the management objective.

Widths for effective sediment removal vary from one metre in relatively well drained flat areas to as much as 60 m in steeper areas with more impermeable soils. On average, almost 70% of sediment can be removed by 5 m wide buffer. Gharabaghi *et al.* (2002) found that almost all course sediment particles were captured in the first 5 m of a filter strip but 90% could be removed with 16-20 m strips. Such high removal efficiencies can be achieved at this width because fine sediments are able to infiltrate into the soil (Gharabaghi *et al.*, 2002). Sediment trapping efficiency did not vary by vegetation type; grass buffers and forest buffers had similar sediment trapping efficiency.

The studies above focused on sediment trapping from overland flow the effectiveness of riparian buffer strips for reducing stream bank erosion are less well studied, especially in New Zealand. A review by Hughes (2016) found that the exclusion of livestock from riparian areas was generally the principal factor in the measured improvements, rather than buffer width or vegetation type. Furthermore, the establishment of riparian vegetation in pastoral catchments may in some circumstances result in channel widening and hence increased sediment input, at least during the phase needed for ‘adjustment’ to the new forest-like conditions (Hughes, 2016).

To maximize biodiversity (Davies-Colley, Payne & Van Elswijk, 2000) found that at least a 40 m buffer is required to achieve comparable air temperatures to native forest. However, Meleason and Quinn (2004) found that 5 m strips could reduce daily maximum temperature from 30°C to 25°C in pasture. Riparian air temperature is equally important to instream temperature for freshwater invertebrates as 50% of adult female stoneflies die at air temperatures of 22-23°C (Collier & Smith, 2000). Collier *et al.* (1995) suggested that a single line of fully grown trees can provide about 80% of shade for small streams and Meleason and Quinn (2004) found even narrow buffers supported healthy stream invertebrate communities in mature plantation Coromandel forest.

Daigneault, Eppink and Lee (2017) suggest that biodiversity gains may only begin at 20 -50 m buffer widths, while Sweeney and Newbold (2014a) meta-analysis concluded that riparian areas should be at least 30 m wide to protect key aspects of forested small stream ecosystems.

The length of the riparian buffer may be more important than the width. (Parkyn *et al.*, 2003) found improvement in invertebrate communities only occurred with temperature decreases associated with full canopy closure Furthermore, patches of remnant forest are often refuges for recolonising stream invertebrate species, meaning that only when riparian buffers and forest patches are connected through riparian corridors (Parkyn *et al.*, 2003). Thus, planting entire stream reaches from the headwaters to the mouth would be the best solution.

The benefits from a given buffer width will also vary with the surrounding land use, soil type, bank slope, type and density of riparian vegetation.

As slope increases, the speed at which water flows over and through the buffer increases. Therefore, the steeper the land within the buffer, the wider it needs to be to have time to slow the flow of water and absorb the pollutants and sediments within it (Hawes & Smith, 2005). In both the USA (Wenger, 1999) and Australia (Barling & Moore, 1994), recommended buffer widths include slope as an integral factor

Buffer width = 15.2 + 0.61 per 1% of slope (m) (Wenger, 1999)

Buffer width = 8 + 0.65 x slope (m) (Barling & Moore, 1994)

(Collier *et al.*, 1995) presented a table to relate land slope, drainage and proportion of soil as clay to the efficiency of buffer strip widths. Generally, buffer widths will have to widen as the slope length, angle, and clay content of the adjacent land increase and as soil drainage decreases.

Similarly soil type affects how quickly water can be absorbed. Soils that are high in clay are less permeable have greater runoff. Conversely, soils that are largely made up of sand may drain water so rapidly into the groundwater that roots are not able to effectively trap pollutants (Hawes & Smith, 2005; Allaire *et al.*, 2015).

Structurally diverse riparian buffers, i.e. those that contain a mix of trees, shrubs and grasses, are much more effective riparian buffers than solely trees or grass (Hawes & Smith, 2005). For example, removal efficiencies range from 61% of the nitrate, 72% of the total phosphorous and 44% of the orthophosphates from grass buffers to 92% of the nitrate 93% of the total phosphorous and 85% of the orthophosphates from combined grass and woody buffers (Jontos, 2004).

Multi-tiered systems are the most popular form of riparian management recommended by regional councils throughout New Zealand. These consist of a combination of buffers, where native trees may be used beside the stream to enhance ecological function and biodiversity, a buffer of production trees may occur outside of that, and a grass filter strip may occur on the outermost edge. The combination of vegetation types (trees, grass and shrubs) helps maximize the efficiency and diversity of benefits that the buffer provides (Borin *et al.*, 2005; Hawes & Smith, 2005; Blanco-Canqui, Gantzer & Anderson, 2006; Balestrini *et al.*, 2011; Aguiar Jr *et al.*, 2015)

8. Will planting up the buffers but keeping the rivers within the inner management line have the same effect?

It is highly unlikely. If constrained the river will continue to erode the planted buffer. It will slow the process but ultimately the river will try to move where it wants to. Furthermore the root depth of many riparian plants is quite shallow and erosion may even undermine below the root line (Fig. 1).

Figure 4 Undercut banks below root zone (Photo A Neverman Landcare)

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References

Abu-Zreig M., Rudra R. & Whiteley H. (2001) Validation of a vegetated filter strip model (VFSMOD). *Hydrological processes,* **15,** 729-742.

Aguiar Jr T., Rasera K., Parron L., Brito A. & Ferreira M. (2015) Nutrient removal effectiveness by riparian buffer zones in rural temperate watersheds: The impact of no-till crops practices. *Agricultural Water Management,* **149,** 74-80.

Aldous A., Fitzsimons J., Richter B. & Bach L. (2011) Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research,* **62,** 223-231.

Allaire S., Sylvain C., Lange S., Thériault G. & Lafrance P. (2015) Potential efficiency of riparian vegetated buffer strips in intercepting soluble compounds in the presence of subsurface preferential flows. *PLoS One,* **10,** e0131840.

Aye T., Nguyen M., Bolan N. & Hedley M. (2006) Phosphorus in soils of riparian and non-riparian wetland and buffer strips in the Waikato area, New Zealand. *New Zealand Journal of Agricultural Research,* **49,** 349-358.

Balestrini R., Arese C., Delconte C., Lotti A. & Salerno F. (2011) Nitrogen removal in subsurface water by narrow buffer strips in the intensive farming landscape of the Po River watershed, Italy. *Ecological Engineering,* **37,** 148-157.

Barling R. & Moore I. (1994) Role of buffer strips in management of waterway pollution: a review. *Environmental Management,* **18,** 543-558.

Barnes J.B., Vaughan I.P. & Ormerod S.J. (2013) Reappraising the effects of habitat structure on river macroinvertebrates. *Freshwater Biology,* **58,** 2154-2167.

Baxter C.V., Fausch K.D. & Saunders W.C. (2005) Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. *Freshwater Biology,* **50,** 201-220.

Benda L., Poff N.L., Miller D., Dunne T., Reeves G., Pess G. & Pollock M. (2004) The network dynamics hypothesis: how channel networks structure riverine habitats. *Bioscience,* **54,** 413-427.

Biron P.M., Buffin-Belanger T., Larocque M., Chone G., Cloutier C.A., Ouellet M.A., Demers S., Olsen T., Desjarlais C. & Eyquem J. (2014) Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience. *Environmental Management,* **54,** 1056-1073.

Blanco-Canqui H., Gantzer C. & Anderson S. (2006) Performance of grass barriers and filter strips under interrill and concentrated flow. *Journal of environmental quality,* **35,** 1969-1974.

Boothroyd I., Quinn J., Langer E., Costley K. & Steward G. (2004) Riparian buffers mitigate effects of pine plantation logging on New Zealand streams: 1. Riparian vegetation structure, stream geomorphology and periphyton. *Forest Ecology and Management,* **194,** 199-213.

Borin M., Vianello M., Morari F. & Zanin G. (2005) Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. *Agriculture, Ecosystems & Environment,* **105,** 101-114.

Brierley G., Reid H., Fryirs K. & Trahan N. (2010) What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. *Science of the Total Environment,* **408,** 2025-2033.

Buffin-Belanger T., Biron P.M., Larocque M., Demers S., Olsen T., Chone G., Ouellet M.A., Cloutier C.A., Desjarlais C. & Eyquem J. (2015) Freedom space for rivers: An economically viable river management concept in a changing climate. *Geomorphology,* **251,** 137-148.

Collier K., Cooper A., Davies-Colley R., Rutherford J., Smith C. & Williamson R. (1995) Managing riparian zones. *A contribution to protecting New Zealand's rivers and streams,* **2**.

Collier K. & Smith B. (2000) Interactions of adult stoneflies (Plecoptera) with riparian zones I. Effects of air temperature and humidity on longevity. *Aquatic Insects,* **22,** 275-284.

Collins A., Naden P., Sear D., Jones J., Foster I. & Morrow K. (2011) Sediment targets for informing river catchment management: international experience and prospects. *Hydrological processes,* **25,** 2112-2129.

Collins R., Donnison A., Ross C. & Mcleod M. (2004) Attenuation of effluent-derived faecal microbes in grass buffer strips. *New Zealand Journal of Agricultural Research,* **47,** 565-574.

Collins R., Mcleod M., Hedley M., Donnison A., Close M., Hanly J., Horne D., Ross C., Davies-Colley R. & Bagshaw C. (2007) Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of*

Agricultural Research, **50,** 267-278.

Collins R., Mcleod M., Hedley M., Donnison A., Close M., Hanly J., Horne D., Ross C., Davies-Colley R., Bagshaw C. & Matthews L. (2010) Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research,* **50,** 267-278.

Corbacho C., Sánchez J. & Costillo E. (2003) Patterns of structural complexity and human disturbance of riparian vegetation in agricultural landscapes of a Mediterranean area. *Agriculture, Ecosystems & Environment,* **95,** 495-507.

Daigneault A., Eppink F. & Lee W. (2017) A national riparian restoration programme in New Zealand: Is it value for money? *Journal of Environmental Management,* **187,** 166-177.

Dankers R., Arnell N.W., Clark D.B., Falloon P.D., Fekete B.M., Gosling S.N., Heinke J., Kim H., Masaki Y., Satoh Y., Stacke T., Wada Y. & Wisser D. (2014) First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences,* **111,** 3257-3261.

Darby S.E. (2010) Reappraising the geomorphology-ecology link. *Earth surface processes and landforms,* **35,** 368-371.

Darby S.E. & Thorne C.R. (1995) Fluvial maintenance operations in managed alluvial rivers. *Aquatic Conservation-Marine and Freshwater Ecosystems,* **5,** 37-54.

Davies-Colley R.J., Payne G. & Van Elswijk M. (2000) Microclimate gradients across a forest edge. *New Zealand Journal of Ecology***,** 111-121.

Davis R.T., Tank J.L., Mahl U.H., Winikoff S.G. & Roley S.S. (2015) The Influence of Two-Stage Ditches with Constructed Floodplains on Water Column Nutrients and Sediments in Agricultural Streams. *Journal of the American Water Resources Association,* **51,** 941-955.

Death R. & Death F. (2014) Ecological effects of flood management activities in Wairarapa Rivers. For Greater Wellington Regional Council, Massey University.

Death R., Fuller I., Death A. & Petrove N. (2017a) Protection of New Zealand native fish habitat - a technique to assess change in river habitat – the eHQI. Massey University, Palmerston North.

Death R. & Joy M. (2015) The plight of New Zealand's freshwater species. Conservation Science Statement No. 1, 14pp. In: *Society for Conservation Biology (Oceania), Sydney*.

Death R.G. (2000) Invertebrate-substratum relationships: do such things occur in New Zealand streams? In: *New Zealand Stream Invertebrates: Ecology and Implications for Management.* (Eds K.C. Collier & M.J. Winterbourn), pp. 157-178. New Zealand Limnological Society, Hamilton.

Death R.G. (2008) Effects of floods on aquatic invertebrate communities. In: *Aquatic Insects: Challenges to Populations.* (Eds J. Lancaster & R.A. Briers), pp. 103-121. CAB International, UK.

Death R.G., Collier K.J., Hudson M., Canning A., Niessen M., David B., Catlin A., Hamer M. & Pingram M.A. (2017b) Does artificial intelligence modelling have anything to offer traditional management of freshwater food resources? In: *Environmental Research Institute,* Hamilton.

Death R.G., Fuller I.C. & Death A.M. (in prep) A technique to assess river habitat change – the missing dimension for water resource management. *Freshwater Science*.

Death R.G., Fuller I.C. & Macklin M.G. (2015) Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology*, **60,** 2477-2496.

Dewalle D. (2010) Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width1. Wiley Online Library.

Elosegi A., Díez J. & Mutz M. (2010) Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. *Hydrobiologia,* **657,** 199-215.

Elosegi A. & Sabater S. (2013) Effects of hydromorphological impacts on river ecosystem functioning: a review and suggestions for assessing ecological impacts. *Hydrobiologia,* **712,** 129-143.

European Commission. (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy., Journal of the European Communities L327, 1-72.

Evans E.P., Ashley R.M., Hall J., Penning-Rowsell E.C., Sayers P., Thorne C.R. & Watkinson A.R. (2004) Foresight Future Flooding, Volume I and Volume II. Office of Science and Technology, London.

Evans E.P., Simm J.D., Thorne C.R., Arnell N.W., Ashley R.M., Hess T.M., Lane S.N., Morris J., Nicholls R.J., Penning-Rowsell E.C., Reynard N.S., Saul A.J., Tapsell S.M., Watkinson A.R. & Wheater H.S. (2008) An update of the Foresight Future Flooding 2004 qualitative risk analysis. Cabinet Office, London.

Faust D.R., Kröger R., Moore M.T. & Rush S.A. (2017) Management Practices Used in Agricultural Drainage Ditches to Reduce Gulf of Mexico Hypoxia. *Bulletin of Environmental Contamination and Toxicology*.

Feld C.K., Birk S., Bradley D.C., Hering D., Kail J., Marzin A., Melcher A., Nemitz D., Pedersen M.L., Pletterbauer F., Pont D., Verdonschot P.F.M. & Friberg N. (2011) From natural to degraded rivers and back again: a test of restoration ecology theory and practice. In: *Advances in Ecological Research, Vol 44.* (Ed G. Woodward), pp. 119-209. Advances in Ecological Research. Elsevier Academic Press Inc, San Diego.

Feld C.K., Fernandes M.R., Ferreira M.T., Hering D., Ormerod S.J., Venohr M. & Gutierrez-Canovas C. (2018) Evaluating riparian solutions to multiple stressor problems in river ecosystems - A conceptual study. *Water Research,* **139,** 381-394.

Fennessy M. & Cronk J. (1997) The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. *Critical reviews in environmental science and technology,* **27,** 285-317.

Fryirs K. & Brierley G.J. (2001) Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. *Geomorphology,* **38,** 237-265.

Fukushima M. (2001) Salmonid habitat-geomorphology relationships in low-gradient streams. *Ecology,* **82,** 1238-1246.

Fuller I.C., Basher L., Marden M. & Massey C. (2011) Using morphological adjustments to appraise sediment flux. *Journal of Hydrology (New Zealand),* **50,** 59-79.

Fuller I.C. & Death R.G. (in press) Framing resilience for river geomorphology: reinventing the wheel? *River Research and Applications*.

Fuller I.C., Richardson J.M., Basher L., Dykes R.C. & Vale S.S. (2012) Responses to river management? Geomorphic change over decadal and annual timescales in two gravel-bed rivers in New Zealand. In: *River Channels: Types, Dynamics and Changes.* (Ed D. Molina), pp. 137-163. Nova Science,, New York.

Fuller I.G. & Death R.G. (2018) The science of connected ecosystems: what is the role of catchment-scale connectivity for healthy river ecology? *Land Degradation & Development*.

Gharabaghi B., Rudra R., Whiteley H. & Dickinson W. (2002) Development of a management tool for vegetative filter strips. *Best Modeling Practices for Urban Water Systems, Monograph,* **10,** 289.

Gibbins C.N., Scott E., Soulsby C. & Mcewan I. (2005) The relationship between sediment mobilisation and the entry of Baetis mayflies into the water column in a laboratory flume. *Hydrobiologia,* **533,** 115-122.

Gilvear D.J. & Winterbottom S.J. (1992) Channel changes and flood events since 1783 on the regulated River Tay, Scotland. *Regulated Rivers-Research & Management,* **7,** 247-260.

Gorski K., Buijse A.D., Winter H.V., De Leeuw J.J., Compton T.J., Vekhov D.A., Zolotarev D.V., Verreth J.a.J. & Nagelkerke L.a.J. (2013) Geomorphology and flooding shape fish distribution in a large-scale temperate floodplain. *River Research and Applications,* **29,** 1226-1236.

Gostner W., Alp M., Schleiss A.J. & Robinson C.T. (2013) The hydro-morphological index of diversity: a tool for describing habitat heterogeneity in river engineering projects. *Hydrobiologia,* **712,** 43-60.

Grantham T.E., Merenlender A.M. & Resh V.H. (2010) Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, U.S.A. *Freshwater Biology,* **55,** 188-204.

Greenwood M.J., Harding J.S., Niyogi D.K. & Mcintosh A.R. (2012) Improving the effectiveness of riparian management for aquatic invertebrates in a degraded agricultural landscape: stream size and land-use legacies. *Journal of Applied Ecology,* **49,** 213-222.

Gregory S.V., Swanson F.J., Mckee W.A. & Cummins K.W. (1991) An ecosystem perpspective of riparian zones. *Bioscience*, **41,** 540-551.

Harding J. (2009) *Stream Habitat Assessment Protocols for wadeable rivers and streams in New Zealand,* University of Canterbury, School of Biological Sciences.

Hart D.D., Johnson T.E., Bushaw-Newton K.L., Horwitz R.J., Bednarek A.T., Charles D.F., Kreeger D.A. & Velinsky D.J. (2002) Dam removal: challenges and opportunities for ecological research and river restoration. *Bioscience,* **52,** 669-681.

Harvey G.L. & Wallerstein N.P. (2009) Exploring the interactions between flood defence maintenance works and river habitats: the use of River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **19,** 689-702.

Hawes E. & Smith M. (2005) Riparian buffer zones: functions and recommended widths. *Eightmile River Wild and Scenic Study Committee,* **15,** 2005.

Helfman G.S. (2007) *Fish Conservation: A guide to understanding and restoring global aquatic biodiversity and fishery resources.*, Island Press, Washington.

Helmers M., Zhou X., Asbjornsen H., Kolka R., Tomer M. & Cruse R. (2012) Sediment removal by prairie filter strips in row-cropped ephemeral watersheds. *Journal of environmental quality,* **41,** 1531-1539.

Hickey M.B.C. & Doran B. (2004) A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. *Water Quality Research Journal of Canada,* **39,** 311-317.

Hill A.R., Vidon P.G.F. & Langat J. (2004) Denitrification potential in relation to lithology in five headwater riparian zones. *Journal of Environmental Quality,* **33,** 911-919.

Holmes R., Hayes J., Matthaei C., Closs G., Williams M. & Goodwin E. (2016) Riparian management affects instream habitat condition in a dairy stream catchment. *New Zealand Journal of Marine and Freshwater Research,* **50,** 581-599.

Houlbrooke D., Horne D., Hedley M., Hanly J. & Snow V. (2004) A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality. *New Zealand Journal of Agricultural Research,* **47,** 499-511.

Hughes A.O. (2016) Riparian management and stream bank erosion in New Zealand. *New Zealand Journal of Marine and Freshwater Research,* **50,** 277-290.

Hynes H.B.N. (1970) *The Ecology of Running Waters.*, University of Toronto Press, Toronto.

Hynes H.B.N. (1975) The stream and its valley. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie,* **19,** 1-15.

Ipcc I.P.O.C.C. (2013) Climate Change 2013: The Physical Science Basis.

Jongman B., Hochrainer-Stigler S., Feyen L., Aerts J.C.J.H., Mechler R., Botzen W.J.W., Bouwer L.M., Pflug G., Rojas R. & Ward P.J. (2014) Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*.

Jontos R. (2004) Vegetative buffers for water quality protection: an introduction and guidance document. *Connecticut Association of Wetland Scientists White Paper on Vegetative Buffers. Draft version,* **1,** 22.

Keedwell R.J. (2005) Breeding biology of Black-fronted Terns (*Sterna albostriata*) and the effects of predation. *Emu,* **105,** 39-47.

Kiss T. & Blanka V. (2012) River channel response to climate- and human-induced hydrological changes: Case study on the meandering Hernad River, Hungary. *Geomorphology,* **175,** 115-125.

Klijn F., Asselman N. & Wagenaar D. (2018) Room for Rivers: Risk Reduction by Enhancing the Flood Conveyance Capacity of The Netherlands' Large Rivers. *Geosciences,* **8,** 20.

Koehn J.D. & Kennard M.J. (2013) Habitats. In: *Ecology of Australian freshwater fishes*

(Eds P. Humphries & K.F. Walker), pp. 81-103. CSIRO Publishing, Collingwood, Vic.

Kondolf G.M. (2000) Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. *Restoration Ecology,* **8,** 48-56.

Lake P.S. (2000) Disturbance, patchiness, and diversity in streams. *Journal of the North American Benthological Society,* **19,** 573-592.

Lee P., Smyth C. & Boutin S. (2004) Quantitative review of riparian buffer width guidelines from Canada and the United States. *Journal of Environmental Management,* **70,** 165-180.

Macklin M. & Harrison S. (2012) Geomorphology and changing flood risk in the UK. Lloyds, London.

Mahl U.H., Tank J.L., Roley S.S. & Davis R.T. (2015) Two-Stage Ditch Floodplains Enhance N-Removal Capacity and Reduce Turbidity and Dissolved P in Agricultural Streams. *Journal of the American Water Resources Association,* **51,** 923-940.

Mankin K., Ngandu D., Barden C., Hutchinson S. & Geyer W. (2007) Grass-shrub riparian buffer removal of sediment, phosphorus, and nitrogen from simulated runoff. *JAWRA Journal of the American Water Resources Association,* **43,** 1108-1116.

Martin T., Kaushik N., Trevors J. & Whiteley H. (1999) Review: denitrification in temperate climate riparian zones. *Water, Air, & Soil Pollution,* **111,** 171-186.

Mayer P., Dwire K., Okay J. & Vidon P. (2014) Featured collection introduction: Riparian ecosystems and buffers II. *JAWRA Journal of the American Water Resources Association,* **50,** 529-532.

Mayer P., Reynolds S., Mccutchen M. & Canfield T. (2007) Meta-analysis of nitrogen removal in riparian buffers. *Journal of environmental quality,* **36,** 1172-1180.

Mcewan A.J. & Joy M.K. (2013) Responses of three PIT-tagged native fish species to floods in a small, upland stream in New Zealand. *New Zealand Journal of Marine and Freshwater Research,* **47,** 225-234.

Meleason M. & Quinn J. (2004) Influence of riparian buffer width on air temperature at Whangapoua Forest, Coromandel Peninsula, New Zealand. *Forest Ecology and Management,* **191,** 365-371.

Naiman R.J. & Decamps H. (1997) The ecology of interfaces: Riparian zones. *Annual Review of Ecology and Systematics,* **28,** 621-658.

Naiman R.J., Decamps H. & Mcclain M.E. (2005) *Riparia: Ecology, Conservation, and Management of Streamside Communities,* Elsevier Academic Press, Amsterdam.

Neilen A., Chen C., Parker B., Faggotter S. & Burford M. (2017) Differences in nitrate and phosphorus export between wooded and grassed riparian zones from farmland to receiving waterways under varying rainfall conditions. *Science of The Total Environment,* **598,** 188-197.

Newson M.D. & Newson C.L. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography,* **24,** 195-217.

Parkyn S. (2004) *Review of riparian buffer zone effectiveness,* Ministry of Agriculture and Forestry Wellington, New Zealand.

Parkyn S., Davies-Colley R., Halliday N., Costley K. & Croker G. (2003) Planted riparian buffer zones in New Zealand: do they live up to expectations? *Restoration ecology,* **11,** 436-447.

Parkyn S., Shaw W. & Eades P. (2000) Review of information on riparian buffer widths necessary to support sustainable vegetation and meet aquatic functions. In: *Prepared by NIWA for Auckland Regional Council.*, p. 38, Vol. 350. Auckland Regional Council, Auckland.

Parkyn S. & Smith B. (2011) Dispersal constraints for stream invertebrates: setting realistic timescales for biodiversity restoration. *Environmental Management,* **48,** 602-614.

Poff L.N., Allan J.A., Bain M.B., Karr J.R., Prestegaard K.L., Richter B.D., Sparks R.E. & Stromberg J.C. (1997) The natural flow regime: a paradigm for river conservation and restoration. *Bioscience,* **47,** 769-784.

Poole G.C. (2010) Stream hydrogeomorphology as a physical science basis for advances in stream ecology. *Journal of the North American Benthological Society,* **29,** 12-25.

Quinn J., Cooper A. & Williamson R. Riparian zones as buffer strips: a New Zealand perspective. In: *Ecology and management of riparian zones in Australia. Proceedings of a National Workshop on research and management needs for riparian zones in Australia, held in association with the 32nd annual congress of the Australian Society for Limnology, Marcoola,* pp. 53-881993.

Quinn J., Steele G., Hickey C. & Vickers M. (1994) Upper thermal tolerances of twelve New Zealand stream invertebrate species. *New Zealand Journal of Marine and Freshwater Research,* **28,** 391-397.

Quinn J., Suren A. & Meurk C. (2003) Riparian management classification for Canterbury streams. *NIWA Client Report MFE01229/0.*

Radoane M., Obreja F., Cristea I. & Mihaila D. (2013) Changes in the channel-bed level of the eastern Carpathian rivers: Climatic vs. human control over the last 50 years.

Geomorphology, **193,** 91-111.

Renouf K. & Harding J.S. (2015) Characterising riparian buffer zones of an agriculturally modified landscape. *New Zealand Journal of Marine and Freshwater Research,* **49,** 323-332.

Resh V.H., Brown A.V., Covich A.P., Gurtz M.E., Li H.W., Minshall G.W., Reice S.R., Sheldon A.L., Wallace J.B. & Wissmar R.C. (1988) The role of disturbance in stream ecology. *Journal of the North American Benthological Society,* **7,** 433-455.

Rice S.P., Lancaster J. & Kemp P. (2010) Experimentation at the interface of fluvial geomorphology, stream ecology and hydraulic engineering and the development of an effective, interdisciplinary river science. *Earth surface processes and landforms,* **35,** 64-77.

Roberts W., Stutter M. & Haygarth P. (2012) Phosphorus retention and remobilization in vegetated buffer strips: a review. *Journal of environmental quality,* **41,** 389-399.

Roley S.S., Tank J.L., Tyndall J.C. & Witter J.D. (2016) How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River Basin? *Water Resources and Economics,* **15,** 43-56.

Sear D. & Devries P. (2008) Salmonid spawning habitat in rivers: physical, controls, biological responses, and approaches to remediation. In: *American Fisheries Society Symposium,* Bethesda, Maryland.

Sear D.A. & Arnell N.W. (2006) The application of palaeohydrology in river management. *Catena,* **66,** 169-183.

Shan N., Ruan X.-H., Xu J. & Pan Z.-R. (2014) Estimating the optimal width of buffer strip for nonpoint source pollution control in the Three Gorges Reservoir Area, China. *Ecological Modelling,* **276,** 51-63.

Sinha R. (2009) The Great avulsion of Kosi on 18 August 2008. *Current Science,* **97,** 429-433.

Stallins J.A. (2006) Geomorphology and ecology: Unifying themes for complex systems in biogeomorphology. *Geomorphology,* **77,** 207-216.

Steward A.L., Marshall J.C., Sheldon F., Harch B., Choy S., Bunn S.E. & Tockner K. (2011) Terrestrial invertebrates of dry river beds are not simply subsets of riparian assemblages. *Aquatic Sciences,* **73,** 551-566.

Sweeney B. & Newbold J. (2014a) Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. *JAWRA Journal of the American Water Resources Association,* **50,** 560-584.

Sweeney B.W. & Newbold J.D. (2014b) Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review. *JAWRA Journal of the American Water Resources Association,* **50,** 560-584.

Thorp J.H., Thoms M.C. & Delong M.D. (2006) The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. *River Research and Applications,* **22,** 123-147.

Thorp J.H., Thoms M.C. & Delong M.D. (2008) *The riverine ecosystem synthesis : toward conceptual cohesiveness in river science,* Academic Press, Amsterdam ; Boston.

Urbanic G. (2014) Hydromorphological degradation impact on benthic invertebrates in large rivers in Slovenia. *Hydrobiologia,* **729,** 191-207.

Vannote R.L., Minshall G.W., Cummins K.W., Sedell J.R. & Cushing C.E. (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* **37,** 130-137.

Vaughan I.P., Diamond M., Gurnell A.M., Hall K.A., Jenkins A., Milner N.J., Naylor L.A., Sear D.A., Woodward G. & Ormerod S.J. (2009) Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation,* **19,** 113-125.

Vaughan I.P. & Ormerod S.J. (2010) Linking ecological and hydromorphological data: approaches, challenges and future prospects for riverine science. *Aquatic Conservation-Marine and Freshwater Ecosystems,* **20,** S125-S130.

Weller D., Baker M. & Jordan T. (2011) Effects of riparian buffers on nitrate concentrations in watershed discharges: new models and management implications. *Ecological Applications,* **21,** 1679-1695.

Weller D., Correll D. & Jordan T. (1994) Denitrification in riparian forests receiving agricultural discharges. *Global wetlands: old world and new***,** 117-131.

Wenger S. (1999) A review of the scientific literature on riparian buffer width, extent and vegetation.

Wheaton J.M., Brasington J., Darby S.E., Merz J., Pasternack G.B., Sear D. & Vericat D. (2010) Linking geomorphic changes to salmonid habitat at a scale relevant to fish. *River Research and Applications,* **26,** 469-486.

Wilby R.L., Beven K.J. & Reynard N.S. (2008) Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes,* **22,** 2511-2523.

Wishart D., Warburton J. & Bracken L. (2008) Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. *Geomorphology,* **94,** 131-152.

Yuan Y., Bingner R. & Locke M. (2009a) A review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. *Ecohydrology,* **2,** 321-336.

Yuan Y., Bingner R.L. & Locke M.A. (2009b) A Review of effectiveness of vegetative buffers on sediment trapping in agricultural areas. *Ecohydrology,* **2,** 321-336.

Zhang X., Liu X., Zhang M., Dahlgren R. & Eitzel M. (2010) A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of environmental quality,* **39,** 76-84.

Zhuang Y.J. & Kidder T.R. (2014) Archaeology of the Anthropocene in the Yellow River region, China, 8000-2000 cal. BP. *Holocene,* **24,** 1602-1623.