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# Managing sediment (dis)connectivity in fluvial systems

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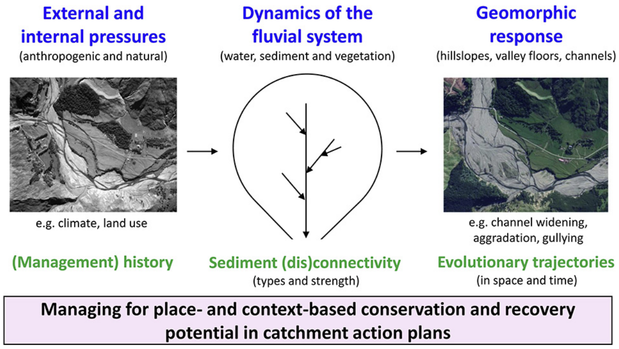
## HIGHLIGHTS

- Managing sediment (dis)connectivity is vital for proactive catchment action plans.
- Geography and history (context) determine catchment-scale (dis)connectivity.
- Human activities modify (dis)connectivity in different ways in different settings.
- Altered (dis)connectivity relationships affect timeframes for geomorphic recovery.
- Catchment-specific understandings are required to manage sediment (dis) connectivity.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Globally, rivers systems are under considerable and increasing threat from multiple anthropogenic stresses, including different types of direct (e.g. channel engineering) and indirect human impacts (e.g. land cover and land use changes) that alter water and sediment dynamics. (Dis)connectivity relationships determine the source, timing and rates of water and sediment flux in catchments and thus their geomorphic sensitivity to disturbance. However, most river and catchment management plans overlook the role of sediment (dis)connectivity. Here we use examples from different environmental settings with different sediment-related problems to show how understandings of sediment (dis)connectivity can inform catchment-based management plans. We focus on concerns for river conservation and recovery, using examples from Austria, New Zealand and Australia. Finally, we present questions for practitioners to consider to appropriately contextualise management applications when using (dis)connectivity concepts in practice. Our findings revealed that differences in sediment (dis)connectivity relationships exert profound catchment-specific variability in (eco)-geomorphic response to disturbance. Understanding (dis)connectivity and system history is therefore essential to forecast the effects of on-ground management actions.

## 1. Introduction

Globally, rivers systems are under considerable and increasing threat from a plethora of anthropogenic stresses (Macklin and Lewin, 2019; Vörösmarty et al., 2010). These include different types of direct (e.g. channel engineering measures) and indirect human impacts (e.g.

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land cover and land use change) that alter flow and sediment regimes (Gregory, 2006; Poeppl et al., 2017; Wohl et al., 2015a). In some parts of the world, rivers are considered to be in a state of recovery from such stresses (Fryirs et al., 2018; Kondolf, 2011). Regardless of which stage of adjustment a river is at, all rivers demonstrate a range of altered states with a variable imprint of legacy, or 'memory' effects that will continue to shape river regime into the future (Brierley, 2010; Wohl et al., 2015a). One such legacy effect is that of anthropogenic disturbance on catchment-scale sediment flux (Evrard et al., 2011; James, 2010, 2013; Poeppl et al., 2015; Walter and Merritts, 2008; Wohl, 2015). Treatment of these legacy effects is often the focus of river and catchment management.

Sediment transfer through river systems is increasingly understood in terms of the connections (or lack thereof) between the many components of the drainage basin – e.g. hillslopes, floodplains, lakes, wetlands, and channels. Sediment (dis)connectivity in catchments is governed by the spatial arrangement of sediment sources, transfer pathways and sinks (the structural component) as well as the interactions between landscape compartments and the frequency-magnitude relationships that dictate the relative effectiveness of geomorphic processes (i.e. the functional component; e.g. Bracken and Croke, 2007; Bracken et al., 2015; Poeppl et al., 2017; Schopper et al., 2019; Wainwright et al., 2011). Catchment-scale (dis)connectivity (longitudinal, lateral and vertical) relationships drive the operation of sediment cascades, exerting a primary control upon the efficiency with which disturbance responses are mediated through catchments (Brierley et al., 2006; Bracken et al., 2015; Fryirs et al., 2007a, 2007b; Fryirs, 2013; Poeppl et al., 2017; Wohl et al., 2019). In turn, this governs the trajectories of geomorphic, habitat and ecological change in river systems (e.g. Boardman et al., 2019; Brierley and Fryirs, 2016; Fausch et al., 2002; Poeppl et al., 2017). Dependent upon contextual considerations (Wohl, 2018), insufficient or excess sediment supply may impact negatively on a range of environmental and/or socio-cultural values (Fryirs and Brierley, 2001, 2016; Hillman et al., 2008). There is growing consensus that (dis)connectivity should form a conceptual basis for informed decision-making in river and catchment management (Keesstra et al., 2018; Wohl et al., 2019). However, to date, most management plans overlooks the role of sediment (dis)connectivity in driving disturbance and treatment responses in rivers and catchments.

In managing for sediment (dis)connectivity, concern lies with both the amount and the composition of sediment in different component parts of the river system. Variation in the prevailing grain size composition of the system may present a range of issues over different timeframes. For example, disturbances within dominantly fine-grained systems may transit the catchment within hours, while transfers through bedload-dominated systems can take decades (e.g. Thompson et al., 2016). The nature of (dis)connectivity dynamics during a small-to-moderate rain or flood event may be quite different from high-magnitude rain or flood events, as pathways become activated or blocked, or switched on and off, at different flow stages (Fryirs et al., 2007a; Fryirs, 2013). The configuration of the river network mediates these linkages, as transport conditions and storage dynamics change at every tributary junction (Benda et al., 2004; Czuba and Foufoula-Georgiou, 2015).

Longitudinal, lateral or vertical disconnectivity can occur at any position along the sediment cascade (Brierley et al., 2006; Fryirs et al., 2007a, 2007b; Fryirs, 2013), potentially impacting the healthy function of abiotic and biotic functions in river systems (Fausch et al., 2002; Vannote et al., 1980; Ward and Stanford, 1995). These disconnections can be either natural or anthropogenic. Natural disconnectors may include wetlands, swamps, and/or floodplains that buffer sediment delivery across various pathways within a catchment. Anthropogenic disconnectors include structures such as dams and reservoirs, stopbanks (artificial/constructed levees) and channelised river reaches. In managing for sediment (dis)connectivity it is often only the disconnectors that can realistically be managed in any given catchment. Examples include land use practices to manage sediment inputs at source (e.g. Prosdocimi et al., 2016; Zhao et al., 2013) or decommissioning of dams and weirs (e.g. Kondolf, 1997; Poeppl et al., 2019a; Warrick et al., 2015).

The above mentioned examples help to emphasise that locally-situated perspectives are important, and place-based applications of connectivity principles are required to inform river management practice (e.g. Hillman et al., 2008; Mould and Fryirs, 2018). Knowing what is being managed, and what we are managing for, is critical in such endeavours. Effective management of sediment (dis)connectivity requires that managers understand the spatial structure, temporal trajectory and the associated dynamics of the sediment cascade for each catchment that is being managed. This entails careful consideration of contextual considerations that determine what is 'expected' in any given system. Some systems are naturally or anthropogenically disconnected at various scales and over various timeframes, while others are more strongly connected (Fryirs, 2013). This foundation knowledge provides the basis to determine, first, whether management is needed at all, and second, if management is needed, what can realistically be managed, where it is best to intervene and the required timeframe for such interventions (Fryirs and Brierley, 2016). Hence, catchment-specific knowledge of sediment (dis)connectivity and system-state/sensitivity is required to inform effective sediment-related river management (Fryirs, 2015; Fuller and Death, 2018; Thompson et al., 2017; Reid and Brierley, 2015).

Once sediment connectivity relationships and the state and trajectory of a system of interest are known, different management options (including location, timing and type of action) and their potential outcomes can be assessed in light of management goals (Lisenby et al., 2019). In relation to river recovery principles, this assessment includes careful consideration of pressures and limiting factors that may enhance or inhibit the potential for recovery and how these can be addressed as part of sediment (dis)connectivity management (Brierley and Fryirs, 2009; Fryirs and Brierley, 2005, 2016; Scorpio et al., 2015; Ziliani and Surian, 2012, 2016). For example, if the system is self-healing due to system-intrinsic processes (e.g. vegetation dynamics and associated recovery of lateral connectivity relationships; Poeppl et al., 2017), precautionary, 'leave it alone' and passive approaches may be appropriate. Elsewhere, the efforts (or time needed) for river recovery may outweigh the benefits of management actions (Fryirs et al., 2018; Kondolf, 2011). Care must be taken to ensure that local interventions do not cause unforeseen off-site impacts (Brierley and Fryirs, 2009). For example, legacy sediment release and associated downstream geomorphic effects following dam removal or impacts of mining, water mills/dams, land use change (e.g. Evrard et al., 2011; James, 2010, 2013; Poeppl et al., 2015; Walter and Merritts, 2008; Wohl, 2015). Depending on the sediment-related problem at hand, different options are available to manage the timing and frequency of sediment flux dynamics, including instream, along-stream or offsite (catchment) measures such as the coordinated operation of dams, dam removal, bank stabilisation, riparian (re)vegetation, or land use/cover changes.

In this paper, we provide some perspective on sediment (dis)connectivity using three real-world case studies drawn from different environmental settings (Europe, New Zealand and Australia) that have been published in the international literature. Our focus here lies not in the construction of sediment budgets that incorporate understandings of sediment (dis)connectivity relationships in each instance. Rather we use these insights to identify the contrasting sediment-related problems encountered in these landscapes and potential management responses. Building on this understanding, we discuss the ways in which sediment (dis)connectivity can inform catchment-based management plans and efforts in differing contexts. Therefore, our case studies focus on the following:

1) System state evaluation: situating each case study to understand the operation of sediment cascades and how human activities have modified sediment (dis)connectivity relationships.

2) Managing river conservation and recovery: identification of catchment-specific, process-based activities and practices for managing sediment (dis)connectivity as part of catchment action plans.

The overarching aim of this paper is to highlight how sediment (dis) connectivity understandings can inform river conservation and recovery programs. The first three sections of this paper present the case studies. Each addresses context and issues, and management options, respectively. Drawing together the findings from the case studies, the discussion addresses the application of sediment (dis)connectivity understandings in river conservation and recovery management. We present a series of questions for practitioners to consider to appropriately contextualise management applications. To close we discuss the role of modelling applications in managing sediment (dis)connectivity.

## 2. Managing sediment (dis)connectivity in Europe – Fugnitz catchment case study

### 2.1. Context and issues – Managing agricultural streams

Following major migrations from the east and southeast around 9000 years ago (i.e. during the Neolithic era), humans have extensively modified water and sediment dynamics in catchment systems across Europe (Davies, 1996). Cumulative impacts have increased markedly over time, accelerating greatly in recent decades. In the second half of the 20th century the status of European rivers chronically deteriorated as increasing anthropogenic pressures such as nutrient pollution and river engineering impacted upon water flow, sediment regimes and river morphology (Grizzetti et al., 2017).

In 2015, 41.1% of the total area in the European Union (EU) was assigned as agricultural land (EC, 2015). Soil erosion is one of the biggest environmental pressures on river ecosystems in agricultural areas. Besides causing severe on-site effects (i.e. soil degradation), water-mediated soil export from the fields to the channel network results in environmental damage such as eutrophication of water bodies (Issaka and Ashraf, 2017; Nadal-Romero et al., 2019), fine-grained sediment accumulation in river channels which clogs and smothers spawning habitats (Walling and Amos, 1999), and sedimentation within reservoirs which reduces water storage capacity (Verstraeten et al., 2006). Knowledge on sediment source areas (i.e. hotspots of soil erosion) and the way they connect to the channel network is therefore essential for environmental management of agricultural streams (Boardman et al., 2019; Poeppl et al., 2019b).

Since the EU adopted the Water Framework Directive (WFD) in 2000, water policy aims to reduce anthropogenic pressures and achieve good ecological status for European water bodies (EU, 2000). The WFD follows a basin-based water and river management approach. For each "river basin district" (RBD) a "river basin management plan" is established which is updated every six years. This entails reported analysis of the characteristics, a review of the impact of human activity on the status of the water bodies, and an economic analysis of water use for each RBD. However, the WFD reports often lack information on soil erosion and lateral sediment input (connectivity) to streams (Hudec et al., 2007). Typically, appropriate modelling tools are unable to appraise inherent spatial and temporal complexity in sediment delivery processes (Bracken et al., 2015; Poeppl et al., 2019b; Rickson, 2014). Moreover, most EU member states do not have specific legislation on soil protection. However, in the Seventh Environmental Action Programme of 2013, the European Commission (EC) recognises that soil degradation is a serious challenge, further committing the EU and its member states to increasing efforts to reduce soil erosion.

### 2.2. Managing lateral fine sediment (dis)connectivity in the Fugnitz catchment

The Fugnitz case study is performed in a medium-sized (ca. 140 km$^2$) temperate agricultural sub-catchment which drains to the Fugnitz River, a mixed-load perennial stream (Fig. 1). The catchment is located in the eastern part of the Bohemian Massif in Austria, near the border with the Czech Republic. Within the Thayatal National Park, the Fugnitz River constitutes the largest tributary of the Thaya River. The underlying bedrock consists of crystalline mica granite and mica shale (Roetzel et al, 2008). Bedrock in the upper and middle reaches is largely overlain by easily erodible loess, alongside sedimentary rocks derived from marine and fluvial depositional environments.

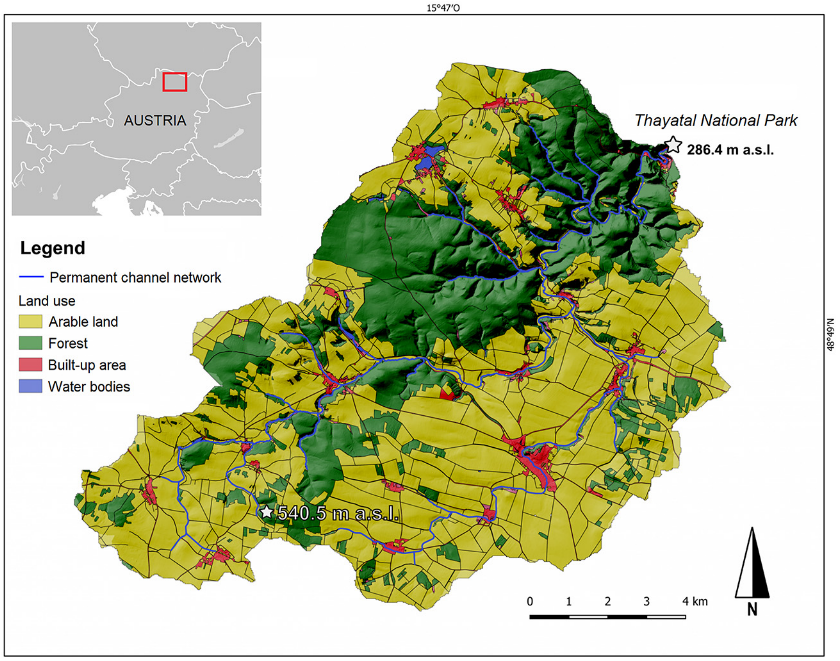

**Fig. 1.** Location and land use of the Fugnitz catchment. Note: a.s.l. = above sea level.
Adapted from Poeppl et al., 2012 and Poeppl et al., 2019b.

Upper and middle parts of the catchment are dominated by agricultural areas (see Fig. 1), mainly cultivation of crops (cereals, lucerne, pumpkin and canola) under conventional management (i.e. ploughing and fertilization; Poeppl et al., 2012). Water-induced soil erosion is common on the steeper hillslopes in the agricultural parts of the catchment.

Land use impacts in the Fugnitz River system induce significant environmental problems for the Thayatal National Park (Fig. 1) This reflects high rates of soil erosion and associated fine-grained sediment and nutrient/contaminant yields from arable fields. Given pronounced lateral connectivity in this system, ready transfer of materials to the river channel network has led to degraded aquatic habitat as fine sediment accumulation clogs or smothers cobble-bed river sections. This is occurring alongside deterioration in biogeochemical water and sediment quality. In response, river recovery concepts have been incorporated within a catchment management plan that includes: 1) system state evaluation (i.e. fine-grained sediment loading and water/sediment quality assessment), 2) soil erosion and lateral sediment connectivity assessment, and 3) development of management/mitigation strategies.

Methods of analysis for this case study work are reported in Poeppl et al. (2015), and Poeppl et al. (2019b). This included bed sediment mapping (Poeppl et al., 2015), water quality assessments (saprobic index (SI) analysis following Moog et al. (2013), Zelinka and Marvan (1961), and ÖNORM M 6232), and soil erosion analysis. The latter incorporated process-based soil erosion prediction modelling that used the (Geo-)WEPP model (Renschler, 2003) to predict average soil loss, determination of sub-catchment sediment yield rates for a 100-year period and field-based mapping of lateral fine-grained sediment connectivity along the main river courses (Poeppl et al., 2019b; based on Poeppl et al., 2012). Finally, the sediment retention efficiency of selected Natural Water Retention Measures (NWRM; EC, 2014) and riparian sediment fences was tested in the field.

### 2.2.1. System state evaluation: fine sediment loading and water/sediment quality

Facies maps show that the middle and lower reaches of the Fugnitz River are generally dominated by coarse bedrock-derived river sediments (i.e. gravel or coarser; Fig. 2). A fine-grained sediment cover is evident in backwater areas and in transport-limited channel sections (Poeppl et al., 2015). Water/sediment quality assessments along five river reaches exhibited a clear downstream deterioration trend in the middle reaches. SI values ranged from 1.55 (“very good”) to 2.73 (“poor”). In contrast, the lower-most reach, located in the lower reaches in the Thayatal National Park, exhibited an SI value of 1.69 (“good”; see Fig. 2).

### 2.2.2. Soil erosion and lateral sediment connectivity assessment

Geo-WEPP modelling combined with field-based lateral sediment connectivity mapping resulted in the delineation of 17 soil erosion and lateral sediment input hot-spots. These are instances where sub-catchments with >2 t/ha/y of sediment yield are connected to the main channel network (Poeppl et al., 2019b.; Fig. 3). Hot-spots are mainly located in the upper and lower middle reaches of the Fugnitz River and its largest tributary (Prutzendorfer Creek; see Fig. 3).

### 2.2.3. Development of management strategies

On-site measures to reduce soil erosion on arable fields are generally based on the following principles (cf. Blanco and Lal, 2008; Boardman and Poesen, 2007): land use according to land capability (e.g. position, soil type), protecting the soil surface (topsoil cover; e.g. mulching), runoff control (e.g. reduction of effective slope length). In Austria (like in most EU member states) there is no specific legislation on soil protection and conservation. Plans that include soil conservation measures for the benefit of down-valley freshwater systems, often occur via

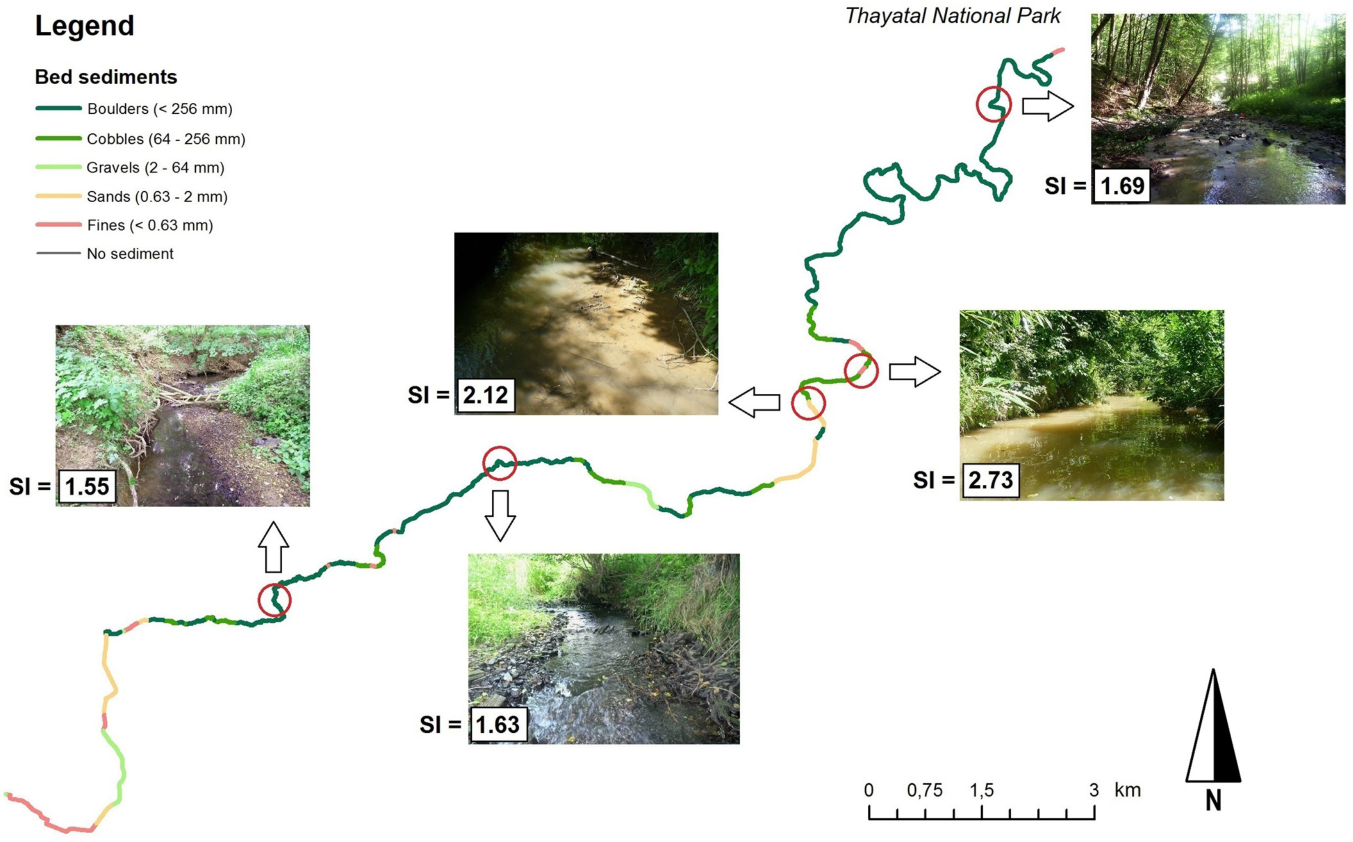

**Fig. 2.** System state evaluation: fine-grained sediment loading (derived from bed sediment mapping; source: Poeppl et al., 2015) and water/sediment quality (derived from SI assessments; source: Scheder and Gumpinger, 2014). Photos: Scheder and Gumpinger (2014; © blattfisch e.U.). See Fig. 1 for river course location.

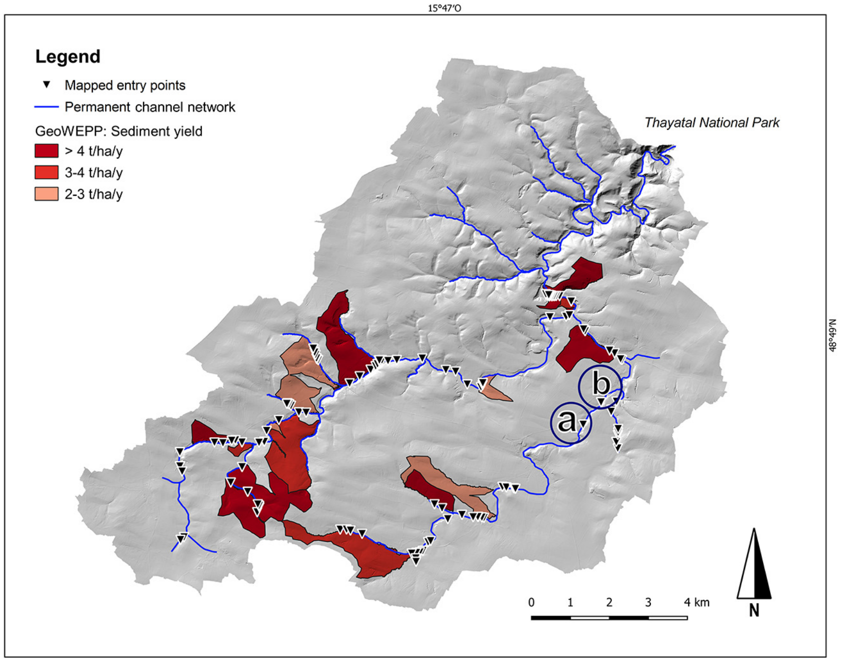

**Fig. 3.** Soil erosion and lateral fine sediment input hotspots (i.e. where sub-catchments with >2 t/ha/y of sediment yield (calculated using the GeoWEPP model) are connected to the main channel network via entry points. Locations of tested NWRM are indicated by blue circles (a) riparian buffer strip; b) silt fence).
Figure adapted from Poeppl et al. (2019a, b).

some form of agro-environmental funding (cf. Boardman et al., 2019). Different types of Natural Water Retention Measures (NWRM) are available to mitigate/manage the off-site effects related to the water-mediated soil export from the fields to the river channel network (Table 1).

**Table 1**
Natural Water Retention Measures (NWRM) as mitigation options selected in the contexts of lateral sediment (and associated nutrient/contaminant) input from agricultural fields to the stream network of the Fugnitz River (i.e. "riparian zone/floodplain options") and in-stream water and sediment retention (i.e. "in-stream options"). Terminology adapted from http://nwrm.eu/ (22.12.2019).

| Natural Water Retention Measures (NWRM) | Explanation |
|---|---|
| 1) Riparian zone/floodplain options | |
| Riparian buffer/filter strips | Riparian buffer/filter strips are areas of natural vegetation cover at the margin of water courses. They act as water infiltration and filter systems that slow surface flow, hence promoting the natural retention of water, suspended solids and associated nutrients/contaminants. |
| Floodplain restoration and management | Measures such as removing of legacy sediment, creation of lakes or ponds, afforestation, plantation of native grasses, shrubs and trees, creation of grassy basins and swales, wetland creation. |
| Sediment capture ponds/dams | Sediment capture ponds are engineered ponds/dams placed in networks of ditches to slow the velocity of water and cause the deposition of suspended materials. |
| 2) In-stream options | |
| Coarse woody debris | Coarse woody debris will generally decrease flow velocity and can reduce the peak of flood hydrographs, further facilitating sediment accumulation. |
| Stream bed/bank re-naturalization/stabilisation | The re-naturalization/stabilisation of river beds and banks can have a high impact on geomorphic channel processes and structural diversity, further facilitating woody debris accumulation, water and sediment retention |

The performance and efficiency of riparian buffer strips and sediment fences as additional mitigation measures has been tested in the field. This was undertaken at two lateral sediment input hotspots (Sites a and b on Fig. 3) following a 36 mm/h rainfall event on June 1st, 2018. This event caused overland flow and associated soil erosion processes. Event-based soil erosion modelling was undertaken using the Geo-WEPP model (Renschler, 2003) for a cornfield where riparian buffer strip sediment retention efficiency investigations have been applied. Results revealed that 2.8 of 5.5 t of modelled total sediment yields have been retained within a 4.5 m wide grassed riparian buffer strip (i.e. 51%), while the rest (i.e. 2.7 t/49%) has crossed the riparian zone and entered the river channel network (Humer, 2020; Table 2; Fig. 4). Similar analyses were applied for a thistle field where sediment fence water and

**Table 2**
Geo-WEPP modelling results and results of riparian buffer strip (Site a)) and sediment fence (Site b)) sediment retention efficiency investigations (incl. information on field and buffer strip characteristics).

| | Site a) | Site b) |
|---|---|---|
| Geo-WEPP modelling results | | |
| Peak runoff | 0.3 $m^3$/s | 0.14 $m^3$/s |
| Soil loss | 8.5 t | 2.8 t |
| Sediment yield | 5.5 t | 2.5 t |
| Field characteristics | | |
| Size | 9.9 ha | 2.6 ha |
| Slope length | 372 m | 230 m |
| Average slope angle | 2° | 2.8 ° |
| Max. slope angle | 10.6° | 5.8 ° |
| Cultivation (height) | Corn (40 cm) | Thistle (20–30 cm) |
| Direction of cultivation/ploughing | Perpendicular (lower slope: parallel) | Perpendicular (lower slope: parallel) |
| Buffer strip characteristics | | |
| Width | 4.5 m | 4 m |
| Height of vegetation | 40–60 cm | 40–60 cm |
| Type of vegetation | Grasses | Grasses |
| Topography | Flat with ruts | Flat |
| Deposited/retained sediment volume | 2.8 t (51%) | - (fence destroyed) |

**Fig. 4.** Riparian buffer strip along a cornfield (after a 36 mm/h rainfall event on June 1st 2018), where buffer strip sediment retention efficiency investigations have been conducted (see Table 2). Photo: Lisa Humer, 2018.

sediment retention efficiency investigations have been conducted. Over a length of 150 m, a 1 m high sediment fence made of filter fleece (150 g/$m^2$, 100% polyester) has been installed at the bottom of a 4 m wide grassed riparian buffer strip (Fig. 5). A peak runoff event of 0.14 $m^3$/s damaged the fence and had a total sediment yield of 2.5 t $m^3$ (see Table 2; see Fig. 5).

These results indicate limited success in attempts to manage lateral sediment connectivity in the Fugnitz catchment using riparian buffer strips and sediment fences in the riparian zone. The capacity of buffer strips to retain sediment yields from mid-magnitude rainfall events was limited, while sediment fences could not withstand associated runoff volumes. Additionally, riparian buffer strips are often bypassed by drainage ditches that collect water and sediment from the fields, directly transporting materials to the channel network (Boardman et al., 2019; Humer, 2020). Such considerations need to be included in lateral sediment connectivity assessments. These findings call for alternative strategies to reduce lateral sediment connectivity as an off-site effect of soil erosion in agricultural catchment systems. This could include NWRM such as strategic installation of water and sediment capture ponds of appropriate size in the riparian zone at hotspots of lateral sediment connectivity. Additionally, re-establishing more natural-like structural habitat conditions, e.g. by removal of channel engineering structures (e.g. Poeppl et al., 2015), or addition/not removing of riparian and instream wood(land) has positive effects on river ecology (e.g. Gurnell et al., 2005). The use of such approaches elsewhere in the Fugnitz Catchment has proven to provide positive results, particularly on natural-like stream reaches, such as the lowermost reach of the Fugnitz River located in the Thayatal National Park. Here the river has a significantly better ecological status than the anthropogenically modified agricultural stream reaches further upstream (see Fig. 2).

## 3. Managing sediment (dis)connectivity in New Zealand – Waiapu catchment case study

### 3.1. Context and issues – managing unruly New Zealand rivers

Implementation of Total Catchment Management principles in New Zealand during the 1950s applied a ‘flushing flow’ mentality through engineering-based ‘command and control’ practices (Knight, 2016). This ‘out of sight, out of mind’ approach to river management simplified the heterogeneity of river systems in efforts to increase the rate of flow and sediment transfer to the coast, accentuating longitudinal connectivity while reducing lateral (channel-floodplain) connectivity. To date, despite long-standing appreciation of erosion and sedimentation issues, and some world-leading work on the morphodynamics of gravel bed rivers, geomorphic understandings and connectivity principles continue to be marginalised, relative to concerns for water quality (Healthy Rivers report, 2019). As noted by Fuller and Death (2018), managing connectivity relations at the catchment-scale should be a critical consideration in ecologically-framed approaches to proactive river management in Aotearoa New Zealand. In many parts of the country, such framings are increasingly challenged by re-assertion of cultural relations to rivers expressed through a ‘living river ethos’ that gives due regard to the behaviour and health of river systems ‘from the Mountains to the Sea’, exemplified by recent application of a Matauranga Māori lens in the designation of river rights to the Whanganui River

**Fig. 5.** Riparian buffer strip with sediment fence along a thistle field, where water and sediment retention efficiency investigations have been conducted (see Table 2). Over a length of 150 m, a 1 m high sediment fence made of filter fleece (150 g /$m^2$, 100% polyester) was installed at the bottom of a riparian buffer strip (left) in March 2018. Destroyed silt fence at an entry sediment point after a 36 mm/h rainfall event on June 1st 2018 (right). Photos: G. Lützenburg, 2018.

(Brierley et al., 2019). Typical of such socio-cultural relations, the Waiapu River lies at the heart of the rohe of Ngāti Porou and is of great cultural significance to its people.

The highly erosive nature of the Waiapu catchment has been a defining management issue since the turn of the century (Phillips and Marden, 2005; Rhodes, 2001). The effects from a major flood in the late 1930s prompted the first of many afforestation schemes, continuing to this day. A Joint Management Agreement signed by the regional council and the local iwi (Ngāti Porou) in 2015 specifically recognises the need to restore and preserve the *mauri* (‘physical life force, vital essence’) and *wairua* (‘non-physical spirit‘) of the Waiapu River. The agreement acknowledges a gradual transfer of powers under New Zealand's Resource Management Act to the local *kaitieke* (the Māori custodians of the watershed).

The trunk stream and tributaries of the Waiapu River have experienced a complex history of response to exceptional rates of sediment recruitment from mass wasting processes over the last 120 years (Barnard et al., 2012; Kasai et al., 2005; Tunnicliffe et al., 2018). An extensive record of valley-scale cross-sections shows remarkable rates of channel aggradation across differing parts of this catchment since Cyclone Bola in 1988. While the typical extent of aggradation has varied from 2 to 5 m in recent decades (Peacock, 2017), local inputs have induced exceptional responses in some instances, with >30 m of bed aggradation within the middle reaches of Raparapariiki Stream over the last few decades (Leenman and Tunnicliffe, 2020; Tunnicliffe et al., 2018).

### *3.2. Managing sediment (dis)connectivity in the Waiapu Catchment on the East Cape of the North Island*

Many challenges are faced in managing sediment flux along the short, steep and unruly rivers of Aotearoa New Zealand. Steep channel gradients commonly extend all the way to the coast (in excess of 1%), presenting significant capacity for sediment reworking and transfer, even in lowland reaches. Rather than operating as ‘regime’ systems (Eaton and Millar, 2017; Wohl et al., 2015a), large transient sediment inputs associated with tectonic (earthquake, volcanic), climatic and anthropogenic disturbance events result in pulsed sediment movement, recurrently altering the aggradational/degradational balance of the system (e.g. Kasai et al., 2005; Tunnicliffe et al., 2018). Extensive flights of fan and terrace complexes attest to the history of bed level changes associated with cycles of aggradation and incision (Fig. 6). Contemporary adjustments related to forest clearance and storm events in the last century are superimposed upon longer term (post-glacial) adjustments and responses to tectonic activity (Marden et al., 2018).

Two major tributaries merge to form the Waiapu River: the Tapuaeroa (‘western’ branch, 1040 km$^2$) and the Mata (‘south’ branch, 326 km$^2$) (Fig. 7). Both the Tapuaeroa and Mangaoporo catchments have generally higher relief, and a much higher incidence of mass wasting features and gully development relative to other parts of the Waiapu Catchment. Despite being three times the size of the Tapuaeroa, the Mata River has a much more quiescent character. The bed gradient of the lower Mata is about 0.0023, which is shallower than most major rivers in the system (Fig. 8). The Tapuaeroa bed gradient is about 0.0070 near its junction with the Mata, an exceptionally energetic system for its catchment area. Extensive aggradation and rapid rates of geomorphic adjustment are evident along the middle and lower Tapuaeroa, middle reaches of the Waiapu, and the middle and lower Mangapaoro. By contrast, the Mata River has less evidence of channel change, and less extensive floodplain development (see Tunnicliffe et al., 2018).

Network configuration, whether viewed as the pattern of tributary-trunk stream relationships or downstream changes in valley confinement (i.e. accommodation space for sediment storage) exerts a critical influence upon rates of sediment conveyance (e.g. Walley et al., 2018). Significant inter-annual variability in the pattern and rate of reworking of materials on fan and aggraded valley floor surfaces recurrently modifies sediment connectivity relationships in these high energy landscapes (e.g. Fuller and Marden, 2011; Marden et al., 2005, 2011).

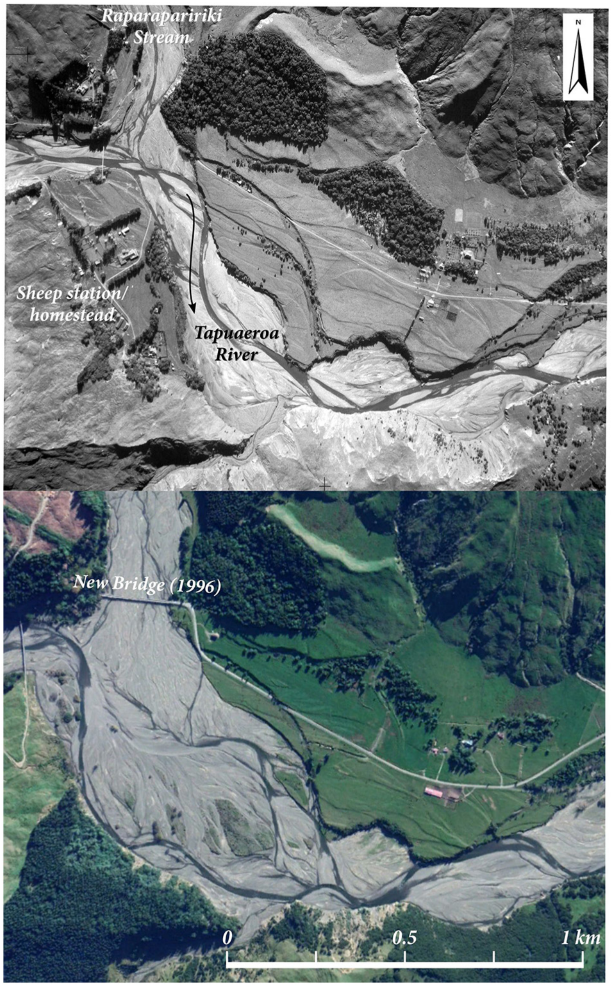

**Fig. 6.** Aggradation-driven changes within the Tapuaeroa River, a major tributary of the Waiapu River. A photo sequence (1939–2019) highlights the dramatic changes at the confluence zone where the Raparapariiki River meets the Tapuaeroa. Flights of terraces evident in the 1939 photo show that the river has been through incisional phases in the past. The reach has been inundated with >6 m of sediment since Cyclone Bola in 1988. The aggradation has buried a sheep station and homestead, as well as other pastured terrace surfaces evident in the earlier imagery. Following the complete burial of a bridge on the Raparapariiki in the early 1990s, a new bridge was constructed (lower photo).

#### *3.2.1. System state evaluation: high rates of coarse sediment delivery*

The high sediment loads within the Waiapu Catchment derive mainly from steep and active hillslopes. Across much of the catchment, uplift of weak rocks and recurrent hillslope failures deliver large amounts of sediment to valley floors. In contrast to rivers draining ‘hard rock’ greywacke or volcanic terrain, high concentrations of fine-grained materials sourced from ‘soft rock’ silt- and mudstones result in extremely high sediment yields. Sediment generation reflects four modes of sediment production and transfer: (1) diffusive slopewash (Fig. 9), (2) shallow failures and landsliding on steeper slopes, (3) gullies and gully complexes (Fig. 10), and (4) deep-seated earthflow movements.

Erosion from gullies and gully complexes within the Waiapu accounts for a disproportionate amount of sediment delivery: they contribute at least 50% of suspended sediment in both the Waiapu and Waipaoa Rivers (Marden et al., 2005; Page et al., 2007). Repeat surveys of headwall areas of gully mass-movement complexes demonstrate profound rates of sediment supply from particular hillslopes, in some instances generating sustained yields on the order of 100,000 m$^3 \cdot$a$^{-1}$

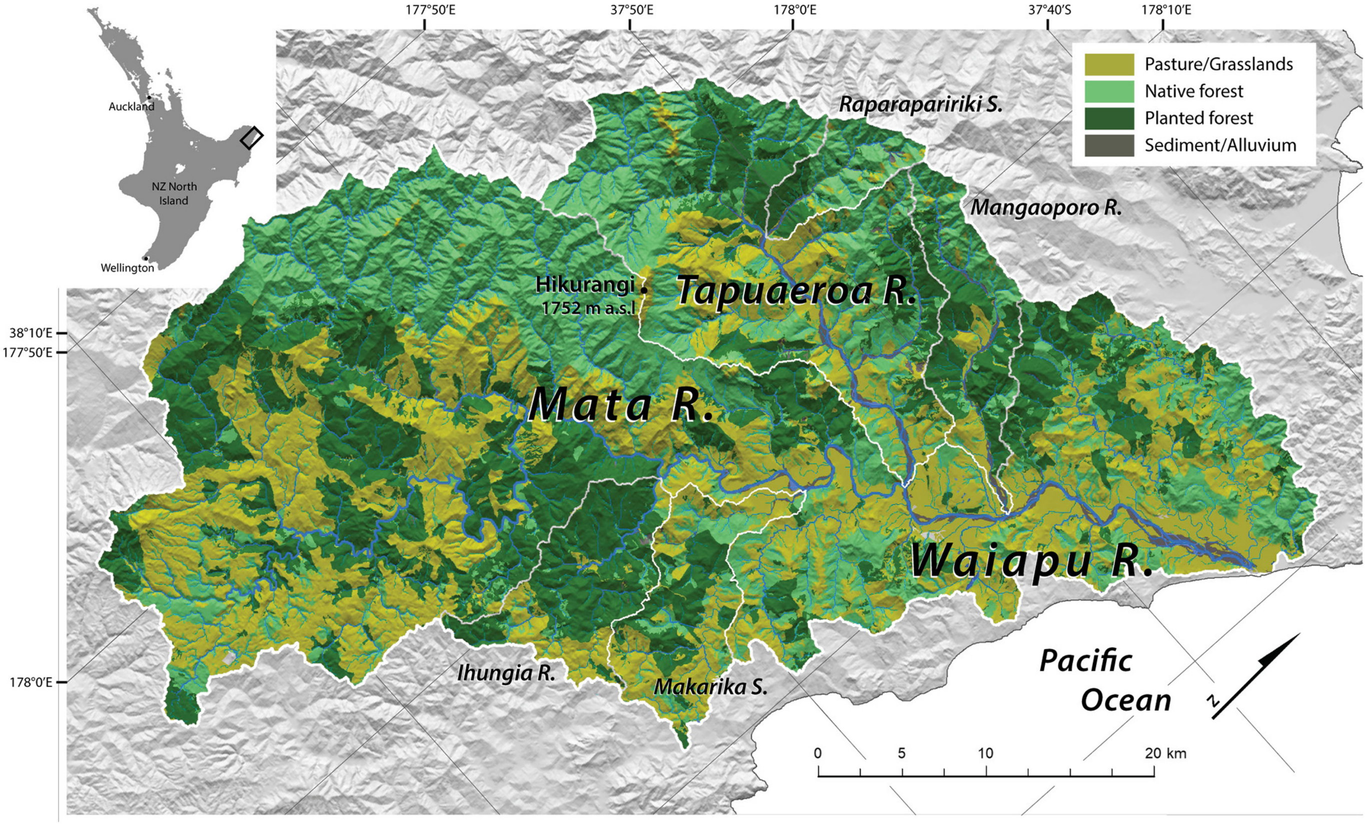

**Fig. 7.** Location and land use of the Waiapu Catchment on the East Cape of Aotearoa New Zealand.

over multiple decades (e.g. Betts et al., 2003; Fuller and Marden, 2011; Leenman and Tunnicliffe, 2018). Localised inputs from landslides, gully mass-movement complexes and tributary systems disrupt longitudinal connectivity, often creating significant bed aggradation (see Fig. 10). This, in turn, accentuates downstream delivery of materials, while acting as a barrier to movement of materials from upstream areas which 'infill' the space along the valley floor created by the changing base level (Tunnicliffe et al., 2018).

Planting of new forest may check gully expansion, although Marden et al. (2005, 2011) point out that for gullies larger than 10 ha, there is limited potential for recovery, and it will tend to be very slow. Gullies of 1–5 ha have a 60% chance of recovering after 30 years (i.e. the

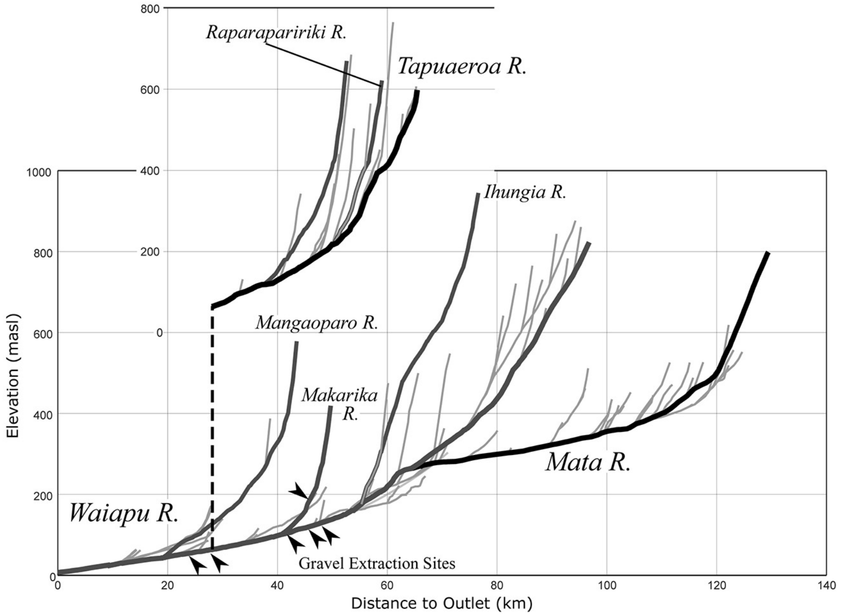

**Fig. 8.** Longitudinal profile of the Waiapu River and its tributaries. Note the relatively suppressed relief of the Mata River relative to other tributaries in the catchment. Gravel extraction has occurred mainly within the Mata, although sediment surplus tends to be found within the main stem of the Tapuaeroa/Waiapu rivers. Higher-order streams are shown in darker shades.

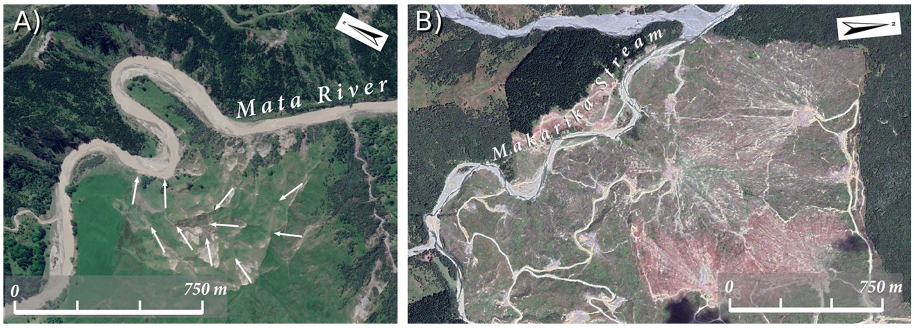

**Fig. 9.** Shallow, diffusive processes on steep slopes. (A) Exposed terrain on weak bedrock is subject to surficial failures. Steep and convergent terrain enhances delivery of material to the channel. (©2019 Maxar Technologies). (B) Cable yarding during forestry operations leaves tracks across steepland terrain; steep and bare slopes are subject to heightened risk of erosion for a 5–8 years following forestry operations, as canopy cover and soil cohesion imparted by root mats from replanted vegetation gradually develops. (©2015 DigitalGlobe).

timescale of forest harvest rotation). For reference, the large gully in Fig. 10A is ~20 ha; Barton's Gully (see Fig. 10B) is 80 ha. Linear gullies are more likely to be stabilised than amphitheatre-shaped gullies.

Ongoing land clearance and forestry operations may temporarily accentuate the delivery of material to the river system, particularly in the absence of riparian margins, in the interval between tree removal and uptake of new growth on hillsides (see Fig. 9b). Following clearance, slash and debris from forestry works may be dispersed along the river network, along with both fine-grained and coarse sediments from steeper slopes.

Fig. 11 shows erosional trends within the Waiapu Catchment in recent decades. This analysis is based on detailed river cross-section measurements collated from 1988 (Cyclone Bola) onward (an associated record of cross-sections measured since 1957 provides an invaluable picture of system dynamism with which to contextualise this analysis). Management issues relate directly to the incidence of gullies and mass wasting activity in the system, which is most prominent in the Tapuaeroa catchment. For example, Raparapariki Stream has aggraded >30 m since Cyclone Bola.

### 3.2.2. Lateral sediment connectivity assessment

Contemporary patterns of valley floor aggradation and longitudinal connectivity in the Waiapu Catchment are dictated by lateral connectivity relationships, particularly the rate of sediment delivery from hillslopes. As shown in Fig. 11, the pattern of landslide activity and gully mass movement processes varies markedly across the catchment, with a particular concentration in the tributaries to the north – the Tapuaeroa and the Mangapaoro. This impacts upon the resultant river morphology and behaviour of these systems, and flooding and erosion problems that ensue.

Many gully systems are closely coupled with the channel along the mainstem of the Waiapu River, constructing fans via both alluvial and debris flow processes. Leenman and Tunnicliffe (2020) show the interplay between sediment supply (upstream controls) and mainstem bed trends (downstream control) that influences fan growth and reworking. Persistent fan growth has significant implications for bank stability. For example, the Mangaoporo/Waiapu confluence (Fig. 12) presents a particularly difficult management issue, as the Waiapu River continuously erodes the toe of a composite earthflow/landslide, periodically reactivating the feature and destabilising essential road infrastructure.

### 3.2.3. Development of management strategies

To date, there have been about 54,000 ha of afforestation in the Waiapu catchment, with remaining target land of 13,526 ha (Barnard et al., 2012). Across the East Coast, over 96% of afforestation in the period from 1993 to 2005 was carried out using *Pinus radiata* (Meister, 2006). While high sediment yields may persist for years after afforestation, vegetating these slopes very effectively arrests shallow landslides and slopewash from susceptible terrain in the long term. The incidence of shallow landslides on steep slopes covered in closed-canopy forest may be up to 90% less than on hillslopes in pasture (DeRose et al., 1998).

Canopy cover is also effective in shutting down gullies, by improving soil infiltration, added soil strength, and increasing interception of rainfall. Herzig et al. (2011) and Marden et al. (2011) found that afforestation schemes have reduced the sediment yield derived from gullies in the Waiapu catchment by approximately 17%.

Table 3 provides an overview of some of the erosion control strategies that have been employed within the region. It is important to emphasise that only a few of these techniques have performed effectively over the long term. It is difficult to deliver truly sustainable results without considering additional knock-on effects, and often conflicting stakeholder interests. Thus, a great deal of care must go into the implementation of such works. More elaborate reinforcement, retention and diversion works tend to be expensive, and require ongoing maintenance. Managing the problem *at source*, rather than in the river, is the critical issue. This includes both open hillsides as well as 'zero-order' basins: the relatively steep convergent zones above the channelized ('first-order') links in the drainage network. Hillslope processes are typically active in these areas. Between major storm events, weathered detritus that collects in these hillslope declivities is primed

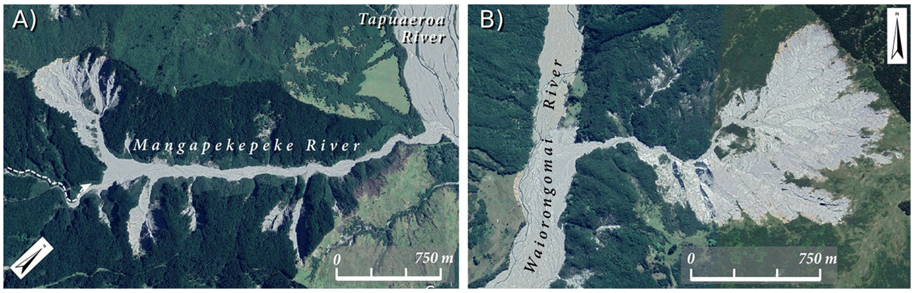

**Fig. 10.** Gully development in hill country within the Tapuaeroa catchment. (A) Mangapekepeke Stream, a right-bank tributary of the Tapuaeroa, changes channel character abruptly as it flows past major gully sites (©2019, Maxar Technologies). (B) Waiorongomai Stream features one of the largest gully complexes in New Zealand: Mangarara Stream, also known as Barton's Gully, has produced roughly 1.2 M $m^3$ of weathered clastic material annually, on average, since the earliest airphoto record (1939) (©2019, Maxar Technologies).

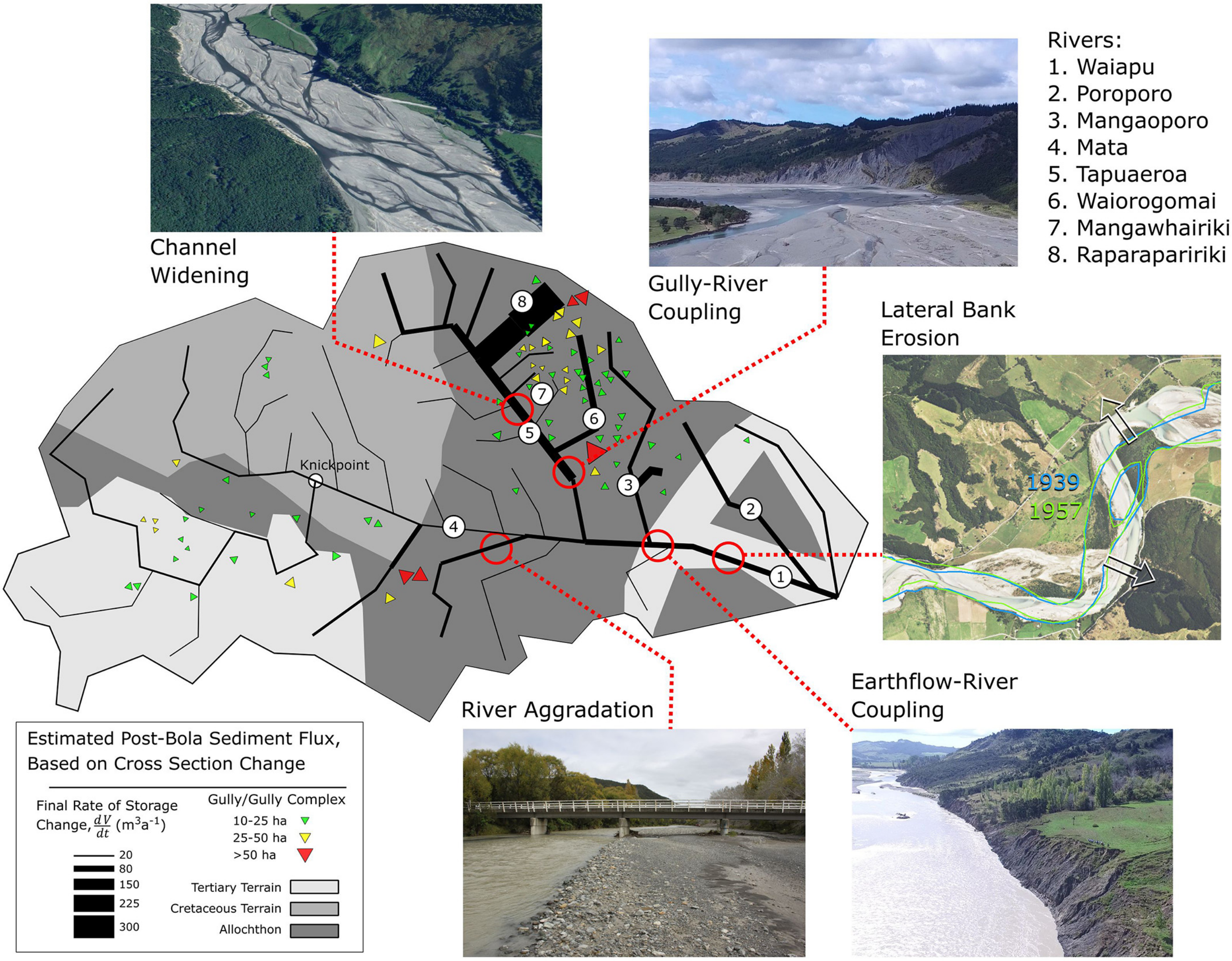

**Fig. 11.** Coupling of major sediment sources in the Waiapu Catchment (based on Tunnicliffe et al., 2018). The thickness of lines along the schematised depiction of the drainage network represents the rate of river cross-sectional change, which is linked to sediment transfer. High rates of aggradation are related to landslide and gully sedimentation. Dynamic channel switching occurs in the wandering reaches of the lower river.

for release in the next event. Canopy cover can be particularly effective at this upper end of the network. The function and effectiveness of riparian buffers and reinforcement changes with scale.

Once in the river system, coarse sediment accumulation becomes more difficult to manage. While the aggradational trend in the river seems to have been arrested, and signs of degradation are emerging, it will take many decades (or centuries) for the river to erode through the deposit, and autocyclic recruitment of terrace material will feed an active sediment regime for decades to come (Tunnicliffe et al., 2018). As more sediment is supplied to the lower river, further active lateral adjustment and loss of currently productive agricultural lands is likely. Thus, prescribing some lands for this adjustment process may be prudent. Another strategy has been to take away gravel via industrial extraction. This can be effective in aggrading systems if carried out carefully and managed in an adaptive manner.

## 4. Managing sediment (dis)connectivity in Australia – Bega catchment case study

### 4.1. Context and issues – managing lazy, sediment exhausted rivers

Southeastern Australia is located in a relatively low relief, passive tectonic setting. Many valleys contain ancient sediments and most rivers are sediment supply limited (Olive and Rieger, 1986; Wasson, 1994). In this land of droughts and flooding rains, Australian rivers have some of the highest flow variability and flash flood magnitude indices in the world (Finlayson and McMahon, 1988). As a result of these landscape and climatic conditions, sediment movement through catchments is pulsed, with many systems experiencing little or no bedload transport for years (or decades during drought). Sediment availability and supply, and (dis)connectivity relationships, are different in southeastern Australian catchments to many other parts of the country and the world (Fryirs, 2013). Sediment dynamics and 'problems' that ensue are accentuated on the valley-bottom, often associated with geomorphic adjustments to river channels. Channel bank erosion is noted as the primary process responsible for sediment delivery to channels, not hillslope supply (Wasson, 1994). Across much of southeastern Australia, hillslopes are largely decoupled from river channels and significant buffering occurs (Fryirs and Brierley, 1999; Fryirs et al., 2007a).

River degradation associated with post-European colonisation and land use practices some 230+ years ago has had a major impact on the geomorphic condition (and associated ecological health) of rivers (e.g. Chessman et al., 2006). In many places the removal of riparian vegetation and wood from streams triggered incision and channel expansion, gully erosion, swamp channelisation, gullying, and disconnection of channels from their floodplains (Brooks and Brierley, 1997; Brierley

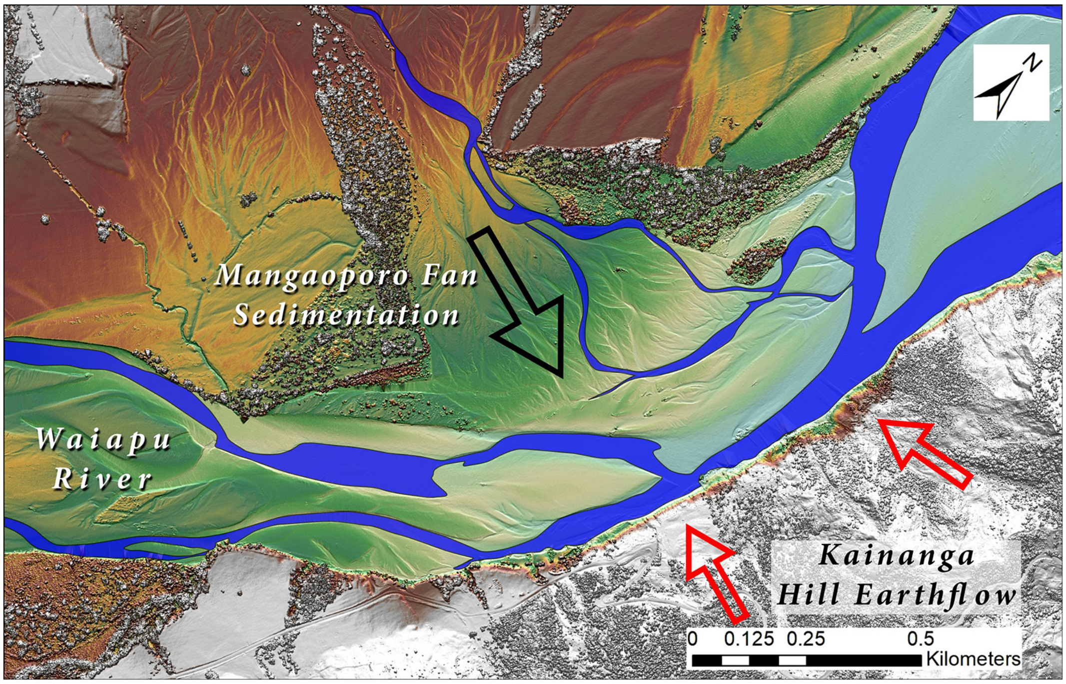

**Fig. 12.** The Mangaoporo Fan, and its impact on valley side stability. Persistent growth of this lateral sediment source pins the river course against the toe of the Kainanga (Kai-Inanga) Hill earthflow complex, resulting in ongoing erosion problems and impacts on a critical transport corridor, a short distance upslope.
Gisborne District Council LiDAR, 2019

et al., 1999; Prosser et al., 2001; Rutherfurd, 2000; Rutherfurd et al., 2001). In some catchments, sediments released from upstream created sediment slugs that have been progressively transferred through systems, and sometimes remain trapped within tributary and trunk stream networks (Bartley and Rutherfurd, 2005; Fryirs and Brierley, 2001; Rustomji and Pietsch, 2007; Sims and Rutherfurd, 2017). At the time of European colonisation, many stream networks were disconnected in terms of sediment conveyance. Swamps, small capacity channels, trapped tributaries and floodplain buffers decoupled many parts of the landscape from the primary sediment conveyor belt. Within decades of European colonisation, many stream networks became sediment connected (or hyper-connected in the case of slugged streams) as valley bottoms were transformed from discontinuous watercourses to continuous channel networks (Brierley et al., 2006). This created an efficient sediment conveyor belt in some instances. Over time, however, sediment exhaustion became a characteristic of some catchments where disturbance and change post-European colonisation was most severe (e.g. Brooks and Brierley, 2004). As a result, geomorphic recovery has only started in the last 30 years, some 200+ years after initial disturbance (Fryirs et al., 2018).

Within a participatory approach to environmental management, a central tenet of community-focussed practice in Australia, Catchment Action Plans (CAPs) from the 1990s onwards have adopted a process-based, recovery-enhancement approach to river management (Fryirs et al., 2013, 2018). Landowners, non-government organisations and community groups work with Local and State government in local-scale on-ground practice, often through public-private-government partnerships. The Bega catchment is an example where this approach has been applied (e.g. Brierley et al., 2002).

Terminology is critical when working with communities and government agencies, and setting policy. River management applications in Australia do not explicitly manage for sediment (dis)connectivity. However, managing for sediment (dis)connectivity is implicit in all passive approaches to management and is framed (and expressed) in terms of ‘keeping the soil on the paddock’, ‘getting the vegetation back on the bench’ (i.e. inset floodplain features that act to contract over-widened channels and increase in-channel roughness), ‘locking up sediment in the right places’, ‘whole of farm management’, ‘natural flood management’, ‘improved water quality and land productivity’, etc. (Fryirs et al., 2018; Thompson et al., 2016).

### 4.2. Managing for sediment (dis)connectivity in the Bega catchment

The Bega sediment budget and sediment (dis)connectivity patterns and changes since European colonisation, along with the history of river evolution, changes in ecological condition and river recovery are well documented in the literature and are not repeated here (e.g. Brooks and Brierley, 1997, 2000; Brierley and Fryirs, 2000, 2009; Brierley et al., 1999, 2002; Chessman et al., 2006; Fryirs and Brierley, 1998, 2000, 2001, 2005, 2016; Fryirs et al., 2007a, 2018; Fryirs, 2013). Fig. 13 summarises some key aspects of this work.

#### 4.2.1. System state evaluation: sediment under-supply and exhaustion in the period since European settlement

The legacy of past land use changes continues to assert a profound impact on the riverscapes of the Bega Catchment. Incision of channels into swamps and tributary fills released nearly 10 million m$^3$ of sediment into the tributary stream network (Fryirs and Brierley, 2001). The overwidening of channels (bank erosion) in both the tributary systems and along the lower truck stream contributed a further 4 million m$^3$ (Fryirs and Brierley, 2001). Along the lower Bega River the channel expanded by over 150% as a result of riparian vegetation and wood removal (Brooks and Brierley, 1997). The majority of the sediment released from the catchment created a sediment slug with an approximate in-channel volume of 8 million m$^3$, with over 4 million m$^3$ of material stored as floodplain sand sheets (Fryirs and Brierley, 2001). As a result of this history, sediment (dis)connectivity patterns in the catchment have switched over time between disconnected (swamps and small capacity channels), to hyper-connected (channel incision and expansion, sediment slug delivery downstream), to weakly-connected (recovery via within-catchment sediment trapping within a supply-limited, sediment exhausted catchment; Fig. 13).

Fig. 13A notes the current-day sediment budget. The thickness of the black lines depicts where readily available sediment sources can

**Table 3**
Approaches to managing sediment flux and connectivity relationships on the East Cape of Aotearoa. This is not an exhaustive list, but illustrates some of the techniques that have been attempted in the past. There is still much work to be done to develop effective solutions that work with the natural dynamism of high-sediment yield river systems.

| Challenges | Proposed response | Issues and Limitations |
|---|---|---|
| 1) Shallow hillslope instabilities | *Close forest canopy, provide root strength, improved infiltration and interception*: | |
| | Fast-growing shrubs and willows | Economics of reversion or forestry vs livestock and range may be challenging. |
| | Poplar and willow poles, indigenous (*nb*. manuka) | Exotic vs indigenous species; slower-growing indigenous is preferred from ecological and aesthetic standpoint, but minimal economic incentive. |
| | Willows in wetter areas, lower on the slope (better adapted to wet environments) - poplars are favoured further up the slope. | |
| | *Keep stock off of stabilising vegetation in susceptible terrain:* | |
| | Fencing. | Expensive with significant maintenance costs |
| 2) Gullies and gully complexes | *Close forest canopy, provide root strength, improved infiltration and interception:* | |
| | Radiata, indigenous species | Issues as above. |
| | Grass, geotextile, aggregate (smaller gullies). | |
| | *Store sediment and/or stormwater, minimizing/staging delivery downstream*: | |
| | Check dams, debris dams, Detention bunds. | Expensive, hard work to install/maintain<br>Dam capacity typically too small to be effective under chronic sediment supply. |
| | *Divert water over/around gully head or scarp slope*: | |
| | Flumes, pipes and chutes | Expensive, hard work to install/maintain. Not always effective, depending on flow pathways and gully form. |
| | Drop structures. | |
| 3) Earthflows | *Close forest canopy, provide root strength, improved infiltration and interception*: | |
| | Fast-growing shrubs and willows | Issues as above; the retention of soil moisture carries pasture growth late into the fall season, or through drought, making this terrain otherwise attractive for grazing livestock. |
| | Poplar and willow poles | |
| | Willow roots form thick mats when in a wet environment. | |
| | *Dewatering; increase the shear strength of the soil* | |
| | Bore holes, taps, drains | Expensive, hard work to install/maintain. |
| | Recontour to improve drainage | |
| 4) In-river strategies | *Recognize that the river floodplain is part of the river:* | |
| | *Remove all critical activities from the floodplain so far as possible* | |
| | Natural river corridor | Ceding land to the river is a difficult proposition for many land owners. |
| | *Bank defenses:* | |
| | Riparian buffer | A contentious issue here is limiting livestock access to the river. |
| | Planting willows, deep-rooting natives, robust grasses | Only effective in limited areas, in a very large floodplain zone |
| | Anchored woody debris | Hard solutions like this tend to deflect the problem to the adjacent bank. Cumulative issues can result from uncoordinated bank defenses. |
| | Riprap, dolos, groynes, spurs | |
| | *Retraining river course* | |
| | Diverting river away from an eroding bank | As above, the erosion situation may be exacerbated, both upstream and downstream, from manipulation of river course. |
| | *Reduce aggradation:* | |
| | Gravel extraction | Habitat impacts in Waiapu are unknown, and likely quite variable. Ecosystems have varying susceptibility both in spatial terms, as well as seasonal.<br>While some drawdown of aggraded valley fill is good, exceeding the bedload supply may lead to incisional trends that propagate up- or downstream. |

enhance river recovery via ‘sediment management’. Sediment (un)availability and (dis)connectivity relationships drive geomorphic recovery prospects in this system. Incised swamps (Fig. 13C), overwidened channels (Fig. 13E) and the sediment slug (Fig. 13F) remain the key river management issues today. Balancing this is protection of unincised swamps (Fig. 13B) and maintenance of rivers that remain in good geomorphic condition (e.g. bedrock-confined reaches; Fig. 13D).

In summary terms, managing rivers for geomorphic recovery in Bega catchment is focussed largely on the longitudinal dimension (upstream-downstream, and tributary-trunk stream), and aspects of the lateral dimension (channel-floodplain) of the sediment conveyor belt. The aim is to first conserve those parts of catchments that remain intact (e.g. swamps) or are in good geomorphic condition. Then, second, enhance disconnectivity by trapping and stabilising sediments within-catchment (in both instream and floodplain compartments) while recognising that with sediment exhaustion ‘every grain counts’ and this process will be a decadal or century long process.

#### *4.2.2. Development of management strategies*

Most river management strategies in the Bega Catchment have applied passive approaches, using vegetation as the ‘engineer’ (sensu Gurnell, 2014). This has been accompanied by changes in land use and farming practices (i.e. fencing-off, stock access and grazing management, weed management). In many cases, the ‘leave it alone’ principle has been used – allowing the system to adjust and self-heal with minimal active intervention.

The reach shown in Fig. 13B is an **unincised swamp** that is characteristic of many of the discontinuous watercourses that occurred in this catchment prior to European colonisation (Fryirs and Brierley, 1998). This swamp at Frogs Hollow and another at Towridgee are the last remaining large-scale swamps in the Bega system. In conservation-first river management practice, such reaches are protected. In terms of management, preventing headcuts from creating incised channels in these valley fills and maintaining sediment disconnectivity and sediment trapping in these parts of the catchment is a high priority (Table 4).

**Fig. 13.** A sediment budget and analysis of pre- and post-European sediment (dis)connectivity patterns informs assessment of river recovery potential across Bega Catchment, helping to provide realistic targets for river conservation and management (Image based on finding from: Brooks and Brierley, 1997, 2000; Brierley and Fryirs, 2000, 2009; Brierley et al., 1999, 2002; Chessman et al., 2006; Fryirs and Brierley, 1998, 2000, 2001, 2005; Fryirs et al., 2007a).

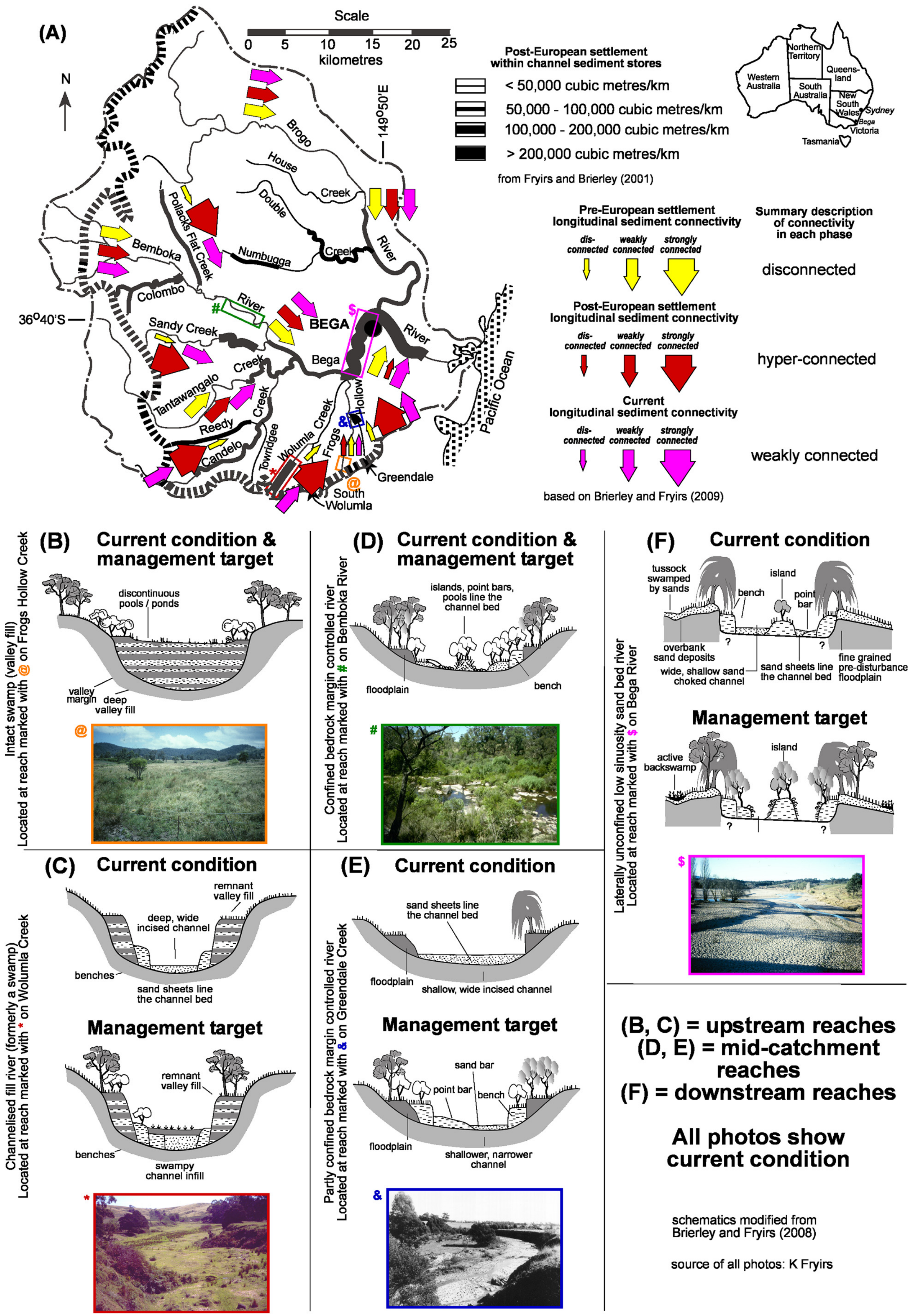
(A)
Scale
0 5 10 15 20 25
kilometres
N
149°50'E
36°40'S
Brogo
House
Creek
Double
Creek
River
Bemboka
Pollacks Flat Creek
Numbugga
Colombo
River
Sandy Creek
BEGA
Bega
River
Tantawangalo
Creek
Reedy
Creek
Candelo
Towridgee
Wolumla Creek
Frogs
Hollow
Greendale
South Wolumla
Pacific Ocean
#
$
&
@
*
Post-European settlement within channel sediment stores
< 50,000 cubic metres/km
50,000 - 100,000 cubic metres/km
100,000 - 200,000 cubic metres/km
> 200,000 cubic metres/km
from Fryirs and Brierley (2001)
Northern Territory
Western Australia
Queens-land
South Australia
New South Wales
Sydney
Bega
Victoria
Tasmania
Pre-European settlement longitudinal sediment connectivity
dis-connected
weakly connected
strongly connected
Summary description of connectivity in each phase
disconnected
Post-European settlement longitudinal sediment connectivity
dis-connected
weakly connected
strongly connected
hyper-connected
Current longitudinal sediment connectivity
dis-connected
weakly connected
strongly connected
weakly connected
based on Brierley and Fryirs (2009)
(B) Current condition & management target
Intact swamp (valley fill)
Located at reach marked with @ on Frogs Hollow Creek
discontinuous pools / ponds
valley margin
deep valley fill
@
(C) Current condition
Channelised fill river (formerly a swamp)
Located at reach marked with * on Wolumla Creek
remnant valley fill
deep, wide incised channel
benches
sand sheets line the channel bed
Management target
remnant valley fill
benches
swampy channel infill
*
(D) Current condition & management target
Confined bedrock margin controlled river
Located at reach marked with # on Bemboka River
islands, point bars, pools line the channel bed
floodplain
bench
#
(E) Current condition
Partly confined bedrock margin controlled river
Located at reach marked with & on Greendale Creek
sand sheets line the channel bed
floodplain
shallow, wide incised channel
Management target
sand bar
point bar
bench
floodplain
shallower, narrower channel
&
(F) Current condition
Laterally unconfined low sinuosity sand bed river
Located at reach marked with $ on Bega River
tussock swamped by sands
island
bench
point bar
?
overbank sand deposits
wide, shallow sand choked channel
sand sheets line the channel bed
fine grained pre-disturbance floodplain
Management target
active backswamp
island
?
$
(B, C) = upstream reaches
(D, E) = mid-catchment reaches
(F) = downstream reaches
All photos show current condition
schematics modified from Brierley and Fryirs (2008)
source of all photos: K Fryirs

**Table 4**
Managing sediment (dis)connectivity in the Bega catchment using a conservation first, recovery enhancement, passive approach to management.

| Challenge | Response | Techniques |
|---|---|---|
| Conserving unchannelised swamps and trapped tributary fills. | Maintaining disconnectivity in some parts of the system. | Leave it alone.<br>Monitor.<br>Headcut prevention and treatment (if needed). |
| Maintaining sediment dynamics in river reaches that are in good geomorphic condition. | Maintaining sediment transport and storage dynamics of these reaches. | Leave it alone.<br>Monitor.<br>Weed management if needed. |
| Managing sediment dynamics in reaches that are in moderate or poor geomorphic condition. | Dependent on river type and position in catchment. Managing connectivity involves assessing where sediment trapping, redistribution and transfer is needed and in what dimensions. | Fencing off (stock access and landuse management).<br>Natural vegetation regeneration.<br>Direct vegetation planting.<br>Weed management. |
| Managing sediment starvation and exhaustion in upstream parts of the catchment where incised channels (ex swamps) occur. | Trapping available sediments on the beds of incised channels. Encouraging reformation of swamps or discontinuous watercourses within the incised channels. | Fencing off (stock access and landuse management).<br>Natural vegetation regeneration.<br>Direct vegetation planting.<br>Weed management. |
| Managing sediment starvation and exhaustion in reaches where overwidened channels occur. | Trapping available sediments on the beds of incised channels. Encouraging reformation of benches that act to narrow channel capacity. | Fencing off (stock access and landuse management).<br>Natural vegetation regeneration.<br>Direct vegetation planting<br>Weed management. |

The reach shown in Fig. 13C is an **incised swamp**. Channel incision into base of escarpment valley fills post-European colonisation occurred in this reach (Wolumla) and in several other valleys including Greendale, South Wolumla, Reedy, Sandy, Colombo, Pollacks Flat and Numbugga (Brierley et al., 1999; Fryirs and Brierley, 2005). Entrenched channels that are up to 100 m wide and 10 m deep are decoupled from floodplains, which have surfaces that are not inundated under the current flow regime (Fryirs and Brierley, 2001). Today, these systems are largely sediment starved and under-supplied. Small volumes of available sediment occur on the incised channel bed and sediment supply from upstream is limited. To enhance river recovery in these systems requires trapping of available sediments in these areas, re-creating swamps and discontinuous watercourses within the incised channels. These 'holes in the landscape' are unlikely to infill over management timeframes of 30–50 years, but recreation of discontinuous watercourse is occurring, enhancing ecosystem values of these rivers (Fryirs et al., 2018). Recovery is supported by fencing-off, stock management and natural swamp vegetation re-establishment (Brierley et al., 2002). Managing for longitudinal sediment disconnectivity is critical in these reaches (Table 4).

The reach shown in Fig. 13D is a **confined bedrock margin controlled river** in good geomorphic condition (Fryirs and Brierley, 2005; Fryirs, 2015). Other examples occur along the upper reaches of Bemboka River and along Tantawangalo, House, Double and Brogo systems. This reach contains large bedrock-based pools, islands and a well-vegetated riparian zone. It is located in the mid-catchment and has escaped much of the geomorphic change that occurred elsewhere in the system in the period since European colonisation. There is some sediment supply available upstream, but this reach has the capacity to transport materials made available to it without infilling pools or impacting on the condition of the reach. Retaining the geomorphic condition of this reach is the priority for river management. This requires maintenance of longitudinal sediment transfer through this reach. Hence, managing longitudinal sediment connectivity is critical in this part of the catchment (Table 4).

The reach shown in Fig. 13E is a poor condition variant of a **confined bedrock margin controlled river** (see reach in Fig. 13D; Fryirs and Brierley, 2005; Fryirs, 2015). Equivalent reaches occur along middle Wolumla, South Wolumla, Candelo, Sandy, Pollocks Flat, Numbugga and the Bega River downstream from the Sandy Creek confluence. In this reach sediment supply from the incision of the upstream swamp post-European colonisation created a sediment slug that has infilled the bedrock-based pools. To accommodate the sediment being transferred through this reach, and associated removal of riparian vegetation, extensive channel expansion and bank erosion has occurred. This supplied additional sediment to this reach and the downstream sediment slug. Managing sediment connectivity in these reaches is graded (not just on or off) and multi-dimensional (both longitudinal and lateral). For these reaches, longitudinal sediment supply from upstream is limited, but some local large-scale stores are available within-reach. Hence, both sediment trapping, redistribution and transfer is a priority within these reaches. To enhance river recovery and improve geomorphic condition requires that some sediment remains locked up (trapped) in these reaches. The formation of benches (inset floodplains) and their stabilisation with vegetation is needed to trigger and enhance channel contraction. Trapping longitudinal sediment inputs in the 'right places' is critical. However, balancing this is the need to also allow longitudinal sediment transfer and reworking/redistribution of sediment within the reach. Flushing of bedrock pools so they 're-emerge' from the sediment slug is a priority (Fryirs et al., 2018). With channel contraction, sediments can be stored on floodplains (and paddocks replenished) by enhancing lateral channel-floodplain connectivity. Recovery can be achieved in these reaches by fencing-off, stock and floodplain property management and direct or indirect re-vegetation, both within-stream (i.e. on benches) and in the riparian corridor (Table 4).

The reach shown in Fig. 13F is a **low sinuosity sand bed river** that contains the sediment slug (Fryirs and Brierley, 2001). The reach is transport capacity limited. Managing sediment problems in this reach has been ongoing for several decades. Like the reach in Fig. 13E, sediment and connectivity management is graded and multi-dimensional. The current channel contains extensive, homogenous sand sheets, some benches and elongate vegetated islands that create an anastomosing-like within-channel planform in places (Brooks and Brierley, 1997). Given that the catchment is now largely sediment supply exhausted, the addition of more sediment to the slug has slowed considerably in the last few decades. Whereas past management strategies sought to enhance longitudinal flushing of this slug to the estuary, priority is now placed on a more nuanced approach to sediment management in this reach, recognising the impact on downstream reaches (and estuarine productivity) should the slug catastrophically move downstream. Like in the reach in Fig. 13E, management now focusses on trapping and enhancing the storage of sediment in well-vegetated islands and benches while allowing for longitudinal connectivity, transfer and removal of small volumes of sediment along the smaller-capacity, anastomosing-like channels (Table 4). Scour on the bed of these channels is locally re-creating pools and riffles. As channel-floodplain connectivity is strong in this part of the catchment, long-term sediment trapping on floodplains (as a sediment sink) is also occurring. A "leave it alone" strategy has largely been adopted for this reach given that it is showing some initial signs of geomorphic recovery.

## 5. Discussion

### *5.1. Using sediment (dis)connectivity understandings in river conservation and recovery management*

Determining what is 'expected' in any given system is a key issue in managing sediment (dis)connectivity at the catchment scale. Some systems such as the Waiapu in New Zealand are overloaded with sediment, while others such as the Bega in southeastern Australia are sediment starved (cf., Brooks and Brierley, 2004; Florsheim et al., 2006; Fryirs and Brierley, 2016; Kondolf, 1998; Kondolf et al., 2001; Smith et al., 2011). Agricultural streams, such as the Fugnitz in Austria (Poeppl et al., 2019b) often have a high fine-grained sediment (and nutrient/contaminant) load derived from soil erosion and sediment transport processes (Owens et al., 2005; Vanmaercke et al., 2011). Differences in sediment (dis)connectivity relationships exert profound variability in the ways and rates with which responses to disturbance events are mediated through a catchment (e.g. Fryirs et al., 2007a; Kuo and Brierley, 2013, 2014; Lane et al., 2008; Surian et al., 2009). In the European example, response is rapid and occurs on an event-by-event basis. The rate of response in the coarser-grained Waiapu (New Zealand) is slower (decadal) reflecting downstream passage of a sediment wave, albeit with more dramatic consequences because of the significant overloading of material. In the case from southeastern Australia the rate of response is lagged even further, occurring over decades to hundreds of years, owing to the low supply rates and the intermittent nature of linkages in the river network. Highly connected systems such as the Waiapu and Fugnitz convey disturbance responses relatively rapidly through the system, while response to disturbance events in disconnected landscapes such as the Bega catchment prior to colonisation may be absorbed within certain parts of the system. Findings from these case studies demonstrate the importance of understanding what is being managed and why. They emphasise the importance of situating sediment (dis)connectivity management within its place-based landscape and catchment context.

Determining what attributes and dimensions of the prevailing sediment regime are manageable (i.e. what is realistically possible), and how we should go about it, are context- and catchment-specific considerations. Such analyses build upon understandings of how human activities have modified (dis)connectivity relationships and how these have altered the evolutionary trajectory of the system (and the consequences/implications thereof; e.g. Fryirs et al., 2007a, 2007b; Poeppl et al., 2017; Vanacker et al., 2005). In some instances, and at different times, rates of movement have been accelerated (e.g. during intense phases of deforestation in Europe or New Zealand, or with the removal of riparian vegetation and wood from Australian streams). Elsewhere, they have been suppressed (e.g. by the installation of dams). In the Fugnitz and Waiapu cases, excess sediments are available to be reworked, and sediment-related problems may ensue in downstream reaches. In such strongly connected, sensitive and thus highly reactive systems, catchment management and river recovery efforts may show relatively immediate effects. Elsewhere (e.g. in southeastern Australia), limited upstream availability of sediment (exhaustion) and highly variable connectivity may inhibit prospects for geomorphic recovery in downstream reaches where channels are over-enlarged. In all these case studies, many reaches are adjusting to legacy anthropogenic effects that have produced either oversupplied or undersupplied systems. The variable nature of these relationships and patterns needs to be taken into account in catchment-specific management programmes.

Although managing for sediment (dis)connectivity is rarely an explicit river management goal, understandings of sediment (dis)connectivity are sometimes used implicitly in proactive, process-based, recovery enhancement approaches (Beechie et al., 2010; Brierley and Fryirs, 2009). This can only occur where catchment-specific understanding of sediment (dis)connectivity patterns and relationships is available. These understandings are required to situate on-ground interventions (or conservation) to improve the (eco-)geomorphic condition of streams. They can be used to guide efforts to attain the best achievable state under prevailing (and future) conditions. Further work is required to relate these sediment (dis)connectivity relations to analyses of nutrients, contaminants, biotic and other biophysical fluxes. Collectively, these are all critical components of integrated approaches to land and water management at the catchment-scale.

Ideally, geomorphologically-informed approaches to risk assessment and planning incorporate flexibility and future variability in the design and implementation of 'moving targets' as open-ended and dynamic goals, relating reach-scale dynamics to understandings of catchment-scale processes and (dis)connectivity relationships (e.g. Brierley and Fryirs, 2009, 2016; Downs and Piégay, 2019; Lisenby et al., 2019; Sear et al., 1995; Toone et al., 2014; Wohl et al., 2015a, 2015b). These geomorphic considerations are key elements of catchment management plans that incorporate concerns for infrastructure protection, resource extraction, land productivity and restoration of ecological processes. Effective sediment management practices apply carefully tailored, process-based solutions that tackle the underlying causes of problems at the appropriate scale, using carefully targeted interventions as required (Wheaton et al., 2019). Blanket applications of the same management practices that disregard these contextual considerations, will not be effective (Spink et al., 2009). Managing (dis)connectivity requires determination of what is 'expected' and realistically achievable in any specific catchment.

### *5.2. Key contextual questions in catchment-scale management of sediment (dis)connectivity*

Proactive programmes identify future sediment-related problems and hazards before they occur, strategically targeting issues before they become a problem. Process-based management practices tackle erosion and sedimentation problems at source, addressing the underlying causes (rather than the symptoms) of these issues. Prevention is cheaper and more effective than cure. In many instances, low cost efforts to negate or minimise negative consequences can have profound long-term benefits and positive off-site effects (Fryirs et al., 2018). For example, nature-based river management solutions such as riparian re-vegetation can be applied to negate negative consequence of accelerated rates of lateral channel migration and excess lateral sediment supply.

When applied effectively, management activities in certain parts of catchments may have catalytic effects by creating or enhancing recovery processes elsewhere in the system. Appraisal of the likely influence of (dis)connectivity relationships upon recovery mechanisms and potential helps to minimise negative off-site impacts of management measures (Schmidt et al., 1998). Of critical importance is knowing when to 'leave it alone' (i.e. passive restoration) versus when to intervene, and where activities in a catchment are likely to be most successful and achieve the 'best bang for the buck' (Fryirs and Brierley, 2016; Fryirs et al., 2018). Such appraisals also help to assess the scale and form of intervention that is required (Wheaton et al., 2019). Building upon principles outlined in Gregory (2006), Fryirs and Brierley (2013), Brierley et al. (2013), Poeppl et al. (2017) and Wohl et al. (2019), key questions to ask in efforts to inform management of sediment (dis)connectivity relations to support river recovery include:

- What is the current system state and how has the system changed in the past? How are/will disturbance responses and management treatments be manifest in a system (e.g. sediment slugs, headcuts on the one hand, construction of sediment retention dams or revegetation activities on the other)?
- What can/should be achieved by managing (dis)connectivity relationships in catchments (i.e. setting targets)? Where can efforts to manage sediment (dis)connectivity be prioritised?

- What sediment issues can be realistically managed? Which tools can be used to manage (manipulate) sediment (dis)connectivity in catchments?
- From where will the sediment be sourced and dispersed to enhance river recovery in the study reach? Is enhancing sediment connectivity required?
- Where should sediment conveyance be suppressed to protect other reaches and minimise off-site impacts? Is enhancing sediment disconnectivity required?
- Which geomorphic trajectories are likely and expected to occur over management timeframes?
- How can the success of different management actions be evaluated?

The case studies outlined in this paper show that answers to these questions play out in different ways. For example, in the Fugnitz and other agricultural catchment systems in Europe where soil erosion and sediment transport processes result in high fine-grained sediment (and nutrient/contaminant) loads, reducing erosion and limiting lateral sediment connectivity is essential for river recovery (cf. Poeppl et al. (2019a, b)). On-site measures to reduce soil erosion include mulching, cover crops, or reduction of effective slope length (e.g. contour management practices). Off-site management options include, but are not limited to, the installation of NWRM such as well-dimensioned vegetated riparian buffer strips (including riparian revegetation), or sediment retention ponds that collect water and sediment from adjacent arable fields and drainage ditches before they enter the channel network (i.e. to disconnect the channels from the catchment area).

Similarly, for most river systems in New Zealand, trapping sediments at source is the key to effective management of sediment flux. This entails minimizing potential for gully mass movement complexes and trapping sediments on the hillslopes before they get into the channel system. This requires careful use of native vegetation with deep and dense root network structures to help hold materials in place, applying carefully targeted applications on and around areas that are susceptible to gully mass-movement processes (Marden et al., 2005). Among numerous initiatives to restore the ecological vitality of the Waiapu river system there are concerted efforts to re-plant erosion-prone land, and moves to diversify land-use in efforts to reduce the sediment load currently reaching the lower reaches – areas with the greatest concern for flood risk and channel instability.

By contrast, in the Bega catchment and similar streams in Australia where sediment availability and supply are now limited, it is imperative to ‘lock-up’ sediments on the valley bottom (both instream and on floodplains). Essentially this entails application of measures to re-disconnect the longitudinal sediment conveyor belt (e.g. Thompson et al., 2016). This includes protection of unincised swamps (Fryirs and Brierley, 2001). Elsewhere, in slugged streams, managing sediment transport alongside sediment stabilisation in strategic locations (e.g. in benches) is key (Bartley and Rutherfurd, 2005; Brierley and Fryirs, 2009; Fryirs and Brierley, 2001; Sims and Rutherfurd, 2017).

### *5.3. The role of modelling applications in sediment (dis)connectivity management*

Readily available remote sensing imagery, alongside modelling and machine learning applications, provide a basis to monitor the forms and rates of system adjustment and connectivity relationships. This presents an opportunity to support cross-scalar applications in which each landscape is allowed to ‘speak for itself’ (Brierley et al., 2013; Brierley, 2020). Changes in structural (dis)connectivity can be quantified at high spatial and temporal resolutions using novel methods such as Structure-from-Motion (SfM) photogrammetry and laser scanning (Turnbull-Lloyd et al., 2018). Various connectivity indices (e.g. the Index of Connectivity (IC) by Borselli et al., 2008; Cavalli et al., 2013) use a combination of topographic and land cover characteristics to determine static representations of connectivity (Turnbull et al., 2018). Different types of model analyse sediment connectivity in relation to sediment dynamics and geomorphic change over time (e.g. Baartman et al., 2013; Coulthard and Van De Wiel, 2017; Masselink et al., 2016). Other models can be used to derive soil erosion rates and lateral input of fine-grained sediment into streams (e.g. Davison et al., 2008; Poeppl et al., 2012; Poeppl et al., 2019b). For example, Coulthard and Van De Wiel (2017) used the cellular-automata CAESAR-Lisflood model to determine changes in sediment fluxes due to the cascading impacts of land use change, and their geomorphic effects on channel changes across large distances and in both upstream and downstream directions. Poeppl et al. (2019b) developed a connectivity-adapted version of GeoWEPP (Renschler, 2003), i.e., “GeoWEPP-C”, to model soil erosion rates and lateral sediment fine sediment input to agricultural streams. In connectivity modelling, or any attempt to “measure” connectivity within catchment systems, recent advances in connectivity research highlight the importance of defining context-specific fundamental units of study among which connectivity relationships can be quantified (Poeppl and Parsons, 2018). CASCADE provides a helpful tool to model sediment movement through river systems (Schmitt et al., 2016), with applications that can inform prospective placement of dams to minimise impacts on sediment connectivity relations at the catchment scale (Tangi et al., 2019). Inevitably, attempts to address each research question or sediment-related management problem are constrained by data availability and resolution.

In general, modelling approaches provide a great opportunity to assess the potential (future) effects of different management practices on water and sediment dynamics in river systems. Conducted effectively, such efforts incorporate appraisal of (dis)connectivity relationships and geomorphic change scenarios. Currently, most model applications are limited in their range of process representation (mainly in-channel sediment transport) and rarely couple water and sediment fluxes with dynamic channel morphological evolution (Poeppl et al., 2019b). As such, they are not specifically designed to be applied in a sediment management context. Moreover, many models are often difficult to use, data demanding, and time- and cost-intensive. Resorting to over-simplified, ill-suited applications is not the answer. These shortcomings call for the development of holistic, easy-to-use (dis)connectivity-based models that can evaluate and quantify the effects of different types of catchment-based or channel-related management actions. Field-based appraisals of sediment connectivity are required to accompany these modelling approaches, and river management in general (Brierley et al., 2006).

## 6. Conclusion

Case studies from Europe, New Zealand and Australia that are outlined in this paper highlight differing catchment management challenges in differing circumstances. They show how understanding sediment (dis)connectivity can inform catchment-based management plans and efforts. The diverse physiographic background and antecedent disturbances within each catchment underscore the importance of understanding sediment (dis)connectivity to appropriately contextualise management applications. The differences in (dis)connectivity relationships exert profound variability in (eco)-geomorphic response to disturbance (high connectivity with rapid response; low connectivity with lagged/slow response). The (dis)connectivity perspective provides five important advantages that can support enhanced management practices:

- Improved appreciation of management timescales and catchment history
- Nuanced understanding and identification of disconnector and linkage points in a catchment
- Capacity for identifying how suppressing/enhancing one or more

linkages, or switching on and off disconnectors may naturally improve conditions elsewhere in the system and prevent negative off-site impacts

- Appreciation of the ways in which water, sediment, nutrients, contaminants, biotic and other biophysical fluxes are interconnected in catchments and along fluvial networks
- Knowledge on system sensitivity required to inform effective sediment-related river management

Determining what attributes and dimensions of the prevailing water and sediment regime are manageable is context- and catchment-specific. This builds upon understandings of how human activities have modified the (dis)connectivity relationships in these systems (system state). Knowledge of (dis)connectivity and system history is therefore essential to forecast the effects of on-ground management actions (e.g. in the context of river conservation and recovery). While modelling approaches provide a good opportunity to assess the potential future effects of different management actions on water and sediment dynamics and associated geomorphic changes in river systems, many models are not yet suitable for broad uptake and usage by river managers, as they are difficult to use, data demanding, and time-and cost-intensive.

## CRediT authorship contribution statement

**Ronald E. Poeppl:**Conceptualization, Writing - original draft, Visualization.**Kirstie A. Fryirs:**Conceptualization, Writing - review & editing, Visualization.**Jon Tunnicliffe:**Writing - review & editing, Visualization. **Gary J. Brierley:**Conceptualization, Writing - review & editing, Visualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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