Framing resilience for river geomorphology: reinventing the wheel?

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Abstract

Resilience is a well-used term in many disciplines, but inconsistently or little applied in river geomorphology, and river science. Recent developments in ecosystem ecology conceptualises resilience as comprising system resistance to, and recovery from, disturbance. The objectives of this paper are to consider how the concept of resilience in this bivariate form applies to river geomorphology, and provide a framework for bridging the disciplines of ecology and geomorphology, within the setting of river management using principles of resilience. River geomorphology sets the physical template upon which lotic processes act, thus understanding the resilience of this template is critical. The importance of consistency in defining principles of resilience thinking within the context of river science and management is important especially when promoting ecosystem resilience as a river management goal. The application of resilience thinking with respect to river habitat is provided through a series of examples from Australian and New Zealand river systems.

Key words: disturbance, river science, river habitat, river ecosystems, process-response

Aim:

How is the concept of resilience applied to river geomorphology, and what does a geomorphologically resilient river look like?

Introduction

Resilience defined

Resilience, like the terms sustainability, heterogeneity and complexity, has multiple uses and interpretations across many a range of disciplines (see Downes et al., 2013; Piégay et al. 2018). Different conceptualisations of a term can help to advance a field of study (Hodges 2008). Holling (1973; 1996) summarises resilience in 'ecological' and 'engineering' terms. Engineering resilience focuses on resistance to disturbance, describing a system near an equilibrium steady state. By comparison, ecological resilience focuses on the magnitude of disturbance that can be absorbed before system structure and function change, and a new regime ensues. The Resilience Alliance defines resilience in terms of system change, where: resilience is the amount of change a system can undergo (its capacity to absorb disturbance, or perturbation) and essentially retain the same function, structure and set of feedbacks (Walker and Salt 2006). The concept of resilience has been increasingly recognised in ecosystem ecology over the past five decades (Hill 1987; Holling 1973; Parsons et al. 2016; Pimm 1984; Walker and Salt 2012; Westman 1978; Wohl 2014; 2016a; Thoms et al., 2018), and is now undergoing a renaissance in a range of fields. However, it has not been widely applied to river systems at a large, or arguably at consistent scales.

At the outset it is necessary to define our conceptualisation of disturbance and perturbation; as any process resulting in or having the potential to effectively change or disrupt the structure and / or function of a system. Perturbation in ecology has traditionally been conceived as something short-term (e.g. a flood event), while disturbance inferred as an event that was more destructive, rare and to all intents and purposes, unrecoverable (Rykiel, 1985). However, this distinction is artificial: perturbation and disturbance are synonymous (Rykiel, 1985), although the language of disturbance (e.g. pulse, press and ramp) has developed in ecology over the past three decades. When crossing disciplinary boundaries, it is important to be clear about the terms employed, and as such we define a disturbance as either a natural process (e.g. flood), or anthropogenic impact (e.g. pollution or structural control) affecting a system. This is consistent with the use of the terms in geomorphology, e.g. Gregory and Lewin (2014) argue that disturbance refers to any externally-driven perturbation.

The capacity of a system to absorb disturbance can be assessed at a range of biophysical, social and economic levels. For example, Parsons et al. (2016) identify fourteen attributes of resilience associated with river ecosystems, including ecological variability, ecosystem services, social capital, governance, feedbacks and thresholds. Thus, Parsons et al. (2016) argue that assessing the resilience of river ecosystems as a whole requires attention to the social, economic and biophysical attributes that confer resilience in river ecosystems. Similarly, Nimmo et al. (2015) recognise that the term 'resilience' in a policy sense in environmental management (e.g. Benson and Garmestani 2011). However Hodgson et al. (2015) argue the measurement of resilience is hampered by taking a broad view that embraces multiple processes, which are often conflicting. They suggest that resilience can be represented by a simultaneous consideration of resistance and recovery, acknowledging that a single metric is insufficient to capture the concept. This is analogous to the concept defined by Nimmo et al. (2015), as resistance-resilience, in which resilience is defined in the sense of capacity to recover from disturbance. Corenblit et al. (2015) also relate the concept of resilience to recovery from, and absorption of disturbance rather than resistance to disturbance (cf. Holling's definition of ecological and engineering resilience).

An important distinction between resistance and resilience is provided by Meyer (2016), who recognises that resistance is related to whether, or the extent to which, system disruption will occur in response to disturbance; while resilience addresses disturbance and system recovery. When disturbed, systems both resist and recover from that disruption or perturbation, and resilience provides a means by which to capture this bivariate idea (Figure 1). Thus Hodgson et al. (2015) define resistance as the immediate impact of externally-driven disturbance on the state of a system, while recovery is the operation of intrinsic processes to restore the system towards, or back to, an equilibrium state. This 'bivariate' approach, which can be used to measure resilience, has recently been welcomed by Yeung and Richardson (2016) as providing an easily understandable representation of the concept, which can be used for ecosystem management. Hodgson et al. (2016) suggest that the study of resilience has suffered from a confusion of terms, metrics and definitions. In this paper, we align with recent suggestions posed in the literature and follow the bivariate approach to defining resilience as a single term proposed by Hodgson et al. (2015). It encompasses system resistance *and* recovery as applied to river geomorphology and in particular channel dynamics.

Figure 1

Objective: reframing for river geomorphology

The purpose of this paper is to consider how the concept of resilience in its bivariate form applies to river geomorphology, and in doing so provide a framework bridging the disciplines of ecology, geomorphology and engineering for use in the holistic management of river systems. Conceptualisation of resilience in these terms is required in order for resilience to be utilised as a way to manage, restore and rehabilitate rivers within the context and challenges posed by global change. This is important because river geomorphology sets the physical template for which lotic processes operate. To understand river ecosystem resilience, the resilience of the physical template that structurally underpins this ecosystem is critical. Loss of, or change in overall physical habitat may be as detrimental to river ecosystem health as degraded water quality or quantity (Elosegi et al. 2010; Elosegi and Sabater 2013). The nature of river ecosystem structure and function, as determined by river geomorphology, is a focal point of key frameworks in stream ecology. These include the River Continuum Concept – RCC - (Vannote et al. 1980), Intermediate Disturbance Hypothesis – IDH - (Connell 1978), Network Dynamics Hypothesis – NDH - (Benda et al. 2004), Shifting Habitat Mosaic – SHM - (Stanford et al. 2005) and the Riverine Ecosystem Synthesis – RES - (Thorp et al. 2006; Thorp et al. 2008). However, the extent to which these frameworks provide an understanding of resilience is not necessarily explicit, or even the focus of such schemes. To advance our knowledge of “healthy”, functioning river ecosystems requires an understanding of the resilience of river geomorphology, but; what is this, and how is it, or how should it be, defined? In the study of the resilience of river geomorphology it is important also to acknowledge the role of biotic components within fluvial ecosystems. River ecosystem resilience is a function of both geomorphology and the collective of biota components. Biotic components respond to physical disturbances but they also influence the magnitude of physical disturbances through various biotic engineering processes. For example Trimble and Mendel (1995) identify the cow as a geomorphic agent, responsible for widening stream channels under heavy grazing; while Statzner et al. (2000) provide evidence for enhanced bed sediment erosion from crayfish activity. Thus an understanding of geomorphic resilience is central to an understanding of river ecosystem structure and functioning and vice-versa: if the physical habitat template is not resilient, nor is the ecology. An example of some of the more frequently used terms in resilience and geomorphology are provided in Table 1.

Table 1

Resilience as a concept in geomorphology

The concept of resilience thinking is implicit in the study of geomorphology (Thoms et al., 2018). Principles of resistance and recovery underpin our understanding of the way geomorphic systems function via inter alia, equilibrium theory (cf. Thorn and Welford, 1994), and the role of extrinsic and intrinsic thresholds (Schumm, 1979), in governing the form and behaviour of landforms (cf. Coates and Vitek 1980). Many of these principles reinforce the paradigm of steady-state equilibrium, which has been a normative concept in geomorphology (Phillips, 2011); especially in stream restoration (e.g. Rosgen 1996). However, Phillips (2011) shows that 'steady-state' conditions are a point along an adjustment continuum, defined by the response of systems to disturbance. The concept of equilibrium in geomorphic systems is based on the notion of balance between process (input variables) and form. Thus when a geomorphic system is disturbed, there is a period of time - relaxation time - during which the system returns to a relative state of balance (Phillips 2014). In river systems, which are prone to disturbance from a range of variable drivers (e.g. storms generating floods and sediment), a truly steady state is unlikely because disturbance intervals tend to be shorter than relaxation time. Thus systems may not trend toward a steady state but rather a state of pseudo-equilibrium, which is normative in most river systems (Phillips 2011). River systems are characterised by constant, or at least repeated, adjustment, tending towards, but never attaining a stable equilibrium. As such, they could be better viewed from an ecological resilience perspective (ie., a high capacity for reorganisation in response to changes in biophysical fluxes), than engineering resilience (cf. Holling 1996). More recently, Knight and Harrison (2014) suggested that Earth surface systems as a whole cannot be considered to exist at a steady state with regard to forcing variables driving their behaviour. This means that change, rather than stability, is the norm in geomorphology (Graf 1979) and specifically in river geomorphology (Gilvear et al., 2016). Change in river systems occurs as either a smooth transition, or an abrupt step-change; the timescale of analysis often determines how these changes appear (Schumm and Lichty 1965). Resilience can be construed as a measure of geomorphological behaviour over a range of spatial and temporal scales. Applying catastrophe theory as a model for describing space-time changes and Graf (1979) illustrated the potential for different behaviours of change in river systems. Graf (1979) hypothesised that a geomorphic system can be described by measures of force and resistance and response, and catastrophe theory indicates that changes taking place in the system can be described as a “cusp catastrophe” (p.20), occurring abruptly or gradually. Essentially this is another way of defining resilience. Here we define resilience as resistance and recovery of systems at a range of spatial and temporal scales in response to disturbance (Figure 1).

Resilience is therefore implicit to fluvial geomorphology, but often with little qualification of its precise meaning (although see Wohl 2016a and Thoms et al., 2018). It has been used to imply the degree of resistance to disturbance or perturbation from flood events, the maintenance of a stable channel form, and stabilisation of riparian structure, at a range of timescales (e.g. Gilvear 1999, Brooks and Brierley 2002, Kasai et al. 2004, Oldmeadow and Church 2006, Collins et al. 2012, , Jackson et al. 2015). Hydrological resilience was defined by Botter et al. (2013) as buffering changes in external forcing. In contrast, Yuill et al. (2016) and Hohensinner et al. (2014) relate resilience to recovery following disturbance, while Buraas et al. (2014) set resilience alongside (in contradistinction to) resistance in the context of channel response to floods. Newson and Large (2006) refer to resilience as a characteristic of natural channels, but do not define the term as such, setting it alongside river function and sensitivity.

From a geomorphological perspective, resilience, as a concept comprising both resistance and recovery, is perhaps best understood in the geomorphological literature in terms of sensitivity, as discussed recently by Wohl (2016a). Frequently used, geomorphic sensitivity has been defined by Brunsden and Thornes (1979) as the relationship between the frequency of disturbance (threshold exceeding) events and the recovery time, which is the time it takes for a system to return to its pre-disturbance condition, in other words its resilience (Phillips 2009). Downs and Gregory (1993) similarly connect sensitivity with the ability of a system to recover from disturbance. Resilience has since been used in conjunction with sensitivity by several authors, either implicitly or overtly (Harvey 2002; Wittenberg and Newson 2005; Thompson et al. 2008; Fryirs et al. 2012; Bruschi et al. 2013; Fryirs et al. 2015; Fryirs 2017). Rice et al. (2012) overtly recognise the relationship between resilience as an ecological concept and geomorphological ideas of reaction, relaxation and response time, which are all used to define system sensitivity. While Phillips and Van Dyke (2016) argue that ‘geomorphic resilience’ relates to dynamical stability and is contingent on how recovery is conceived or defined. This definition refers to the capacity to recover to or towards a pre-disturbance state, with systems better able to recover being more resilient. This definition of a resilient system was also recognised by Wohl (2014), who tracked the adoption of ecological concepts of resilience, sustainability and ecological integrity by fluvial geomorphologists since 2000, in attempts to characterise river health. Resilience is becoming recognised by many as a desirable working concept in river management, e.g. Wohl (2016a), but exactly what is being desired when fluvial geomorphologists speak of the need to improve resilience? Does this mean to improve sensitivity and propensity for change; or enhance recovery following disturbance; or enhance resistance to minimise disturbance in the first place? Downs et al. (2013) argued that the most natural (least modified) reaches of the Santa Clara River, California, were the most morphodynamically resilient, since these stretches, while responding to floods by channel widening, lacked sufficient sensitivity to generate a persistent and recognisable response. This is in contrast to more modified reaches, which suppress morphodynamic sensitivity, but which enhance process sensitivity due to greater sediment transport capacity (Downs et al. 2013). A similar situation has been observed in New Zealand by Fuller and Basher (2013), where the largest recorded flood in the upper Motueka River (Good Friday, April, 2005) resulted in minimal channel planform change due to rock-lined banks, but enhanced sediment transfer, and in fact bed degradation, in the narrowed river corridor. As Downs et al. (2013) point out, the potential for morphodynamic sensitivity in such cases is very high should embankments or (in the case of the Santa Clara River) grade control structures fail during a flood event that exceeds design capacity. Resilience in these engineered rivers is thus forced, rather than inherent as a system property. In this paper we discuss the application of a reframed view of resilience to river geomorphology. We consider how geomorphic resilience, together with thresholds and trajectories can be conceptualised as part of this application. This leads the way to discussing what a geomorphologically resilient river may look like and how rivers should be managed for resilience, particularly in an era of global change. Our discussion is amplified by the use of discrete case studies for illustration.

Resilience applied to river geomorphology

River morphology is influenced by a range of variables, operating at multiple scales (Schumm, 1998). These include the flow regime (the magnitude and variability of discharges, which relate to the prevailing climate regime, and the history of flows), slope, sediment supply and the textural character of the sediment (related to catchment geology), riparian vegetation and bank composition (e.g. alluvium or bedrock). These variables provide boundary conditions that determine how river channels respond to disturbance, such as a large flood or tectonic activity (e.g. the 2010-2011 Christchurch earthquake sequence in New Zealand resulted in base level change and lateral spreading impacting the Avon River –see Fuller et al. 2016). The combination of variables determining river morphology vary continuously, both spatially and temporally, producing a continuum of channel forms in a catchment (Schumm 1977; Fryirs and Brierley 2013). Within a particular river reach, changes to the assemblage and composition of morphological units, e.g. bars, riffles, pools and runs, and changes in the textural character of the river bed substratum in response to floods are determined by the initial sediment texture and channel morphology (Thorp et al. 2006; Poole 2010; Elosegi and Sabater 2013). These scales – the morphological unit and substrate scale – represent critical physical habitat for in channel biota, and the health of river ecosystems. The concept of resilience is best applied to river geomorphology at these scales, recognising that river character / type is characterised by a particular assemblage of these units (Fryirs and Brierley, 2013). At the reach scale or morphological unit scale, resilience is thus the propensity of a river to retain its characteristic assemblage of channel features / units following disturbance. This notion is central to the Shifting Habitat Mosaic Concept (SHMC) of Stanford et al., (2005), which recognises that different fluvial units may have different geomorphic resiliences. In effect, this is the capacity of the river geomorphology to both resist and recover from disturbance, or ‘absorb’ disturbance without substantial change to overall form (Figure 2) at this scale. In (pseudo-) equilibrium terms, this has been recognised as dynamic equilibrium (Hack 1975).

Figure 2.

Geomorphic resilience, thresholds & trajectories

The capacity of a river to absorb (resist and recover from) disturbance is connected to geomorphic thresholds in discrete river reaches. River channel changes occur when thresholds relating to stream power, or flow regime and sediment regime are exceeded (Schumm 1979). Where a river reach lies close to a geomorphic threshold it is primed for change (i.e. it is sensitive to change), which is triggered by disturbance (Brewer and Lewin 1998, and see Schumm 1969; 1979). In such a situation, resistance to change is low, and channel adjustment occurs. Recovery to a disturbance may be rapid (Figure 2), with characteristic morphological units quickly re-established – here vegetation colonisation and development may also play a role (e.g. Dollar at al. 2007; Caruso et al. 2013) and provide a link with riverine plant ecology. The potential relationship between resistance and recovery in generating system resilience is shown in Figure3, where various resilience trajectories are described. The resilience trajectory of a reach is dependent upon its sensitivity to disturbance, and in turn conditioned by its proximity to a threshold (Brunsden and Thornes 1979; Brunsden 2001). A disturbance that fails to exceed a threshold will result in no change in unit structure, river morphology or physical habitat. In this situation resilience is ‘static’ (cf. Figure 3c) and may describe the behaviour of river geomorphology to small, frequent floods. These smaller (within-channel) floods, which can occur c.14-30 times a year in humid temperate environments (Harvey et al. 1979) are critical for maintaining suitable habitat and ecological integrity. These flow events prevent substratum armouring, fine sediment accumulation and excessive periphyton proliferation that can cause cascading trophic changes and reduce ecological condition (Clausen and Biggs 1997; Poff et al. 1997; Death 2008; Lessard et al. 2013), despite having little effect on reach-scale geomorphology. By comparison, larger floods represent potentially greater disturbance, which can be catastrophic in nature (Fuller 2008; Death et al. 2015). Where recovery is rapid, resilience can be considered as 'steady state' (Figure 3a), because the system has absorbed the disturbance and returned to its pre-flood condition (i.e. channel form and assemblage of morphological units). In this case, resistance and recovery are balanced, and since the system absorbs the disturbance, this could be considered as resilience in its classic sense. Based on an assessment of gauged reaches, Phillips and Jerolmack (2016) argue that channels adjust their shape so that floods only slightly exceed sediment transport thresholds, which they suggest is a mechanism of self-organisation. As such, steady-state resilience could be considered as an endemic trait in river geomorphology. In contrast, a catastrophic response to flooding can also occur, resulting in complete transformation of reaches (e.g. Schumm and Lichty 1963, Hauer and Habersack 2009, Thompson and Croke 2013). The notion of steady-state or static resilience does not apply in such circumstances. Although this is timescale-dependent (cf. Schumm and Lichty, 1965), and raises the possibility that resilience in geomorphology must be viewed across multiple timescales (Thoms et al., 2018), albeit spatially at the reach / morphological unit scale. However, this need not necessarily imply that such rivers are not resilient. Phillips (2009) argues that if the pre-disturbance state of a system is not restored, a system can be construed as non-resilient, or having low resilience. Nevertheless, resilience is itself dynamic (Figure 3b), where progressive change occurs in a system adjusting to new boundary conditions, as has been discussed in Schumm's (1969) model of channel metamorphosis, e.g. a progressive increase in discharge and bed load may increase channel width, width:depth ratio, meander wavelength and channel gradient, while reducing sinuosity. I In the East Coast Region of New Zealand, where land-use change has rendered catchments prone to erosion, rivers have been more dramatically transformed from narrow, single-thread systems to rapidly aggrading multi-thread rivers (Page et al. 2007). While in many cases such a change proceeds over several decades, centuries, or even millennia, in one particular East Coast river, the Raparapaririki, the system was transformed within a decade (Tunnicliffe et al. 2018). The transformation of this channel was associated with a major storm event in 1988, and the shift in channel type provides a contemporary example of meta-stable resilience (Figure 3d), which Werritty (1997) referred to as responsive behaviour. Here, steady-state resilience would be categorised as robust. In resilience thinking, robustness would be expected to equate to resilient channel behaviour. However, meta-stable resilience is, arguably, not resilience in the conventional sense because the disturbance has not been absorbed, the system has not recovered, nor resisted, but responded to the disturbance, crossed critical geomorphic thresholds and been transformed to a new channel type, with the prospect of recovery unlikely at a centennial scale (Tunnicliffe et al. 2018). Resilient rivers are thus robust rivers using Werritty's (1997) definitions. Transformative (responsive) change occurs in rivers sensitised to disturbance, sitting close to thresholds (Brewer and Lewin 1998), or in rivers that are subject to wholesale regime change (e.g. Page et al., 2007, Tunnicliffe et al., 2018). Case study 1 provides an example of different trajectories (i.e. directions) of river channel change in the Lower River Murray, South Australia.

Figure 3.

Case Study 1.

The relationship between disturbance frequency, rate of recovery and amplitude of response is important, as it contributes to understanding resilience in the context of river geomorphology (Figure 4). It is important to note that the resulting system dynamics can be considered resilient regardless of how dynamic they are. Highly dynamic rivers, sensitive to small floods, which absorb disturbance and do not experience changes in the assemblage of unit morphologies exhibit robust behaviour (Werritty, 1997), are resilient as moderately dynamic or steady state rivers. In this case, each adjusts to the frequency of disturbance, amplitude of response and rate of recovery that are inherited from the catchment boundary conditions.

Figure 4.

Geomorphologically resilient rivers

What do geomorphologically resilient rivers look like? How should rivers be managed for resilience? A range of river types and dynamics can be considered resilient, especially where disturbance is absorbed and river form retained or recovered. However, not all resilient rivers are necessarily healthy rivers, particularly where river management has sought to maintain a stable channel form with naturally occurring change and propensity for that change being seen as undesirable (Raven et al. 2010; Fuller and Basher 2013). Healthy rivers are those that manifest diversity and complexity of expected form (Wohl, 2016b). These 'messy rivers' have a natural capacity to adjust in response to disturbance, which makes them resilient. The range of natural capacity for adjustment will be dependent upon the character of each river system (cf. Fryirs and Brierley, 2013). As such, both dynamic and non-dynamic river types in their natural state are resilient to the natural range of disturbance (i.e. floods) in their catchment. In its unaltered condition, a river responds with resilience to even the largest floods, because its natural form and character will adjust and recover over time. The problem for river management is that many rivers are now no longer in a natural catchment setting. The following discusses application of the theoretical understanding of resilience as a concept in fluvial geomorphology to inform and improve river management.

Resilience and river management

Traditional river management deliberately homogenises reaches, reducing form complexity and habitat diversity (Wohl 2016a). The end product is robust and insensitive rivers with a largely fixed form (Fuller et al. 2012; Fuller and Basher 2013), at least over short and medium timescales until a “catastrophic flood” occurs. These rivers have suppressed morphodynamic sensitivity (Downs et al. 2013) and could be argued to be highly resilient, because there is no morphological response to most disturbances. But resilience in these systems is largely a product of resistance, since change, and therefore recovery, is often minimal. In fact such reaches lack the capacity to adjust naturally to disturbance, require large-scale investment to maintain their modified form and are vulnerable to wholesale change in the event of infrastructure failure (Downs et al. 2013, Fuller and Basher 2013) and are then very expensive to reinstate. Such forced resistance is not conducive to river health, since habitat diversity is severely curtailed and the shifting habitat mosaic effectively stabilised. Furthermore, there is a significant risk of major geomorphic change in these forced resilient systems, should engineering fail (Downs et al. 2013). A critical debate here is the respective resilience, especially in a period of environmental change, of heavily managed rivers and more natural counterparts. An example of resilience and managing rivers is provided in Case Study 2.

Case Study 2

Rehabilitating for resilience

River rehabilitation focused on resilience is to increase the capacity for recovery. This concerns both the improvement of the recovery in time and space, and minimising the likelihood of large-scale system change to a new state or costly periodic management interventions such as dredging. A resilient river geomorphology is not characterised by zero change or static geomorphology, but by disturbance, response and recovery, and, inevitably, a degree of complexity (Wohl 2016a). To allow for this, most engineered rivers require ‘room to move’. This concept has been advocated in terms of an ‘erodible river corridor’ (Piégay et al. 2005); ‘freedom corridor’ (Biron et al. 2014, Buffin-Bélanger et al. 2015); and ‘protected mobility corridor’ (Choné and Biron 2016). It entails working with nature and respecting geomorphic diversity (Brierley and Fryirs 2009). Importantly, permitting movement means allowing for lateral mobility or channel migration, which are important for maintaining and redistributing sediment (Rinaldi et al. 2013) and sustaining resilience within the system. This in turn connects with physical habitat, because redistribution of sediment means the riverbed is being turned over and pool-riffle units and bars, which develop or are maintained as sediment is redistributed, provide important biotopes and habitat, enhancing biodiversity (Milan et al. 2010; Michalková et al. 2011; Garcia et al. 2012). At a finer scale, mobilisation of riffle sediments is particularly important as this prevents clogging by fine sediment, which is detrimental to ecology – indeed here low resistance to disturbance provides habitat resilience to elevated suspended sediment loading from disturbed catchments. Bank erosion itself is also of benefit to the functioning of river ecosystems (Florsheim et al. 2008) and is a key channel adjustment mechanism during flood disturbance events (Fuller 2008, Phillips and Jerolmack 2016). Indeed, bank erosion allows rivers to increase their capacity as floods become larger and more frequent. Bank erosion linked to lateral migration of meanders also leads to the development of point bars that provide niche habitats for some plants and animal species, and is thus a component of river resilience that should be biologically valued. This process relates to the shifting habitat mosaic, which is an established concept in the functioning of natural ecosystems (Stanford et al. 2005)

Revegetation is important for the rapid recovery of fluvial surfaces to the pre-disturbance state following perturbation (Gurnell 2014, Gurnell et al. 2016). In this sense healthy, resilient riverine landscapes are those which supply pioneer species via hydrochory (e.g. Tererai et al. 2015). Without such a process, change from meandering to wandering and wandering to braided river morphologies is more likely, given the stabilising influence of revegetation. In turn these planform changes pose challenges for river management, as the erodible river corridor width increases without the stabilising and / or limiting effect of revegetation. However, in New Zealand, recent invasion of river corridors by exotic weed species including willow, lupin, gorse and broom has inhibited natural river dynamics in historically active gravelly rivers (native vegetation grows much more slowly than exotic weeds). For example, the Waitaki River, a naturally active braided river in North Otago, has been stabilised significantly by invasive riparian vegetation (Caruso et al. 2013). This vegetation has altered channel and bar dynamics, and associated river habitat and in this case choking of the active channel by invasive vegetation has arguably reduced resilience. To illustrate this point, the Kiwitea Stream in the North Island of New Zealand responded catastrophically to a 100 year annual recurrence interval (ARI) flood in 2004 (Fuller 2008). The reason for this catastrophic response lay in the over-narrowed channel, lined by extensive exotic vegetation (Fuller and Heerdegen 2005). In much the same way as the River Tay, Scotland, responded to a shift in flood regime, the river in this narrowed form was unable to accommodate the 100 year ARI event. The river morphology and attendant river habitat was transformed (Figure 5). Subsequent river engineering has reduced active channel width, but not to the same degree as prior to 2004. The outcome is a wider river corridor, with a diversity of habitat that is more resilient, since both disturbance and recovery are now allowed for. In this example, the resilience capacity has been improved relative to the 1995 channel and the likelihood of subsequent catastrophic transformation been reduced.

Figure 5.

Prospect

Rivers will be exposed to greater frequencies and magnitudes of disturbance with future climate change and predicted increases in frequency and magnitude of extreme events (e.g. Donat et al., 2016). This change can be considered as pulse, ramp or press in nature, following Lake (2000). Changing climate is likely to increase flood magnitude and storminess, which equates to increasing pulse disturbance (Phillips and Van Dyke 2016); as recently seen in Haiti and North Carolina with Hurricane Matthew in October 2016 (Figure 6). However, increased frequency and magnitude of floods constitutes a ramp disturbance, as the strength of the disturbance increases over time (Lake 2000) (Figure 7). Ultimately, these changes may result in a press disturbance, where disturbance regime changes. In sensitive systems, press disturbance results in permanent change in boundary conditions, responsive change takes place, and resilience changes (cf. meta-stable resilience, Figure 3). Since geomorphic sensitivity and resilience relate to the magnitude and frequency of disturbance (Brunsden and Thornes 1979, Brunsden 2001, Phillips and Van Dyke 2016), the relationship between disturbance and response will potentially change as frequency and magnitude change. Schumm (1998) recognised that sensitivity adjusts over space and time, and Fryirs (2013) noted that systems can become more or less sensitive to future disturbances. In turn, a change in sensitivity may effect a change in resistance to disturbance, and thus resilience (Figure 7). In each of the scenarios depicted in Figure 7, resilience is likely to change. It is difficult to predict whether, as Fryirs (2013) suggests, some systems may become more resilient, while others more sensitive. The outcome will be dependent on the magnitude-frequency of disturbances and the inherent characteristics and sensitivity of the system. Where reaction and relaxation time exceed the frequency of disturbances, the system is unable to recover and a ramped response is likely (Figure 7). In such a scenario, resilience, i.e. the ability to absorb disturbance, may be compromised and change in river geomorphology (unit assemblage and channel form) is likely.

Figure 6.

Figure 7.

There is a need to allow for rivers to adjust to changing sediment flux and flow conditions to ensure properly functioning, suitably complex, resilient systems are maintained. Resilience or river sensitivity is not static. Trying to keep river channels as they are today, while the driving forces and boundary conditions that are responsible for these channels and their assemblage of morphological units change within the catchment is not tenable and does not foster resilience in river geomorphology. Instead, change must be anticipated, erosion permitted, adjustment allowed, and complexity in river form, which engenders diversity of river habitat and healthy river ecosystems (Wohl 2016a) must be recognised in framing resilience for river geomorphology. The *rate* of change can be mitigated by strategic and targeted catchment management, taking into account catchment connectivity. For example, reforestation can help reduce some flood peaks and certainly help reduce sediment flux by reducing slope erosion. These measures may slow down the rate of change in river geomorphology, but cannot, ultimately prevent change altogether. Managing for complexity and resilience at a reach-scale, so that adjustments can take place and disturbance absorbed, can be facilitated or enhanced by an holistic approach to catchment management. This requires an understanding of resilience at a larger spatial scale, a ‘network resilience’, which recognises that connectivity within the contributing catchment is fundamental to maintaining the natural scope of river adjustments and response to perturbation (e.g. Fryirs 2013). Where connectivity is disrupted at a catchment scale, resilience at a reach-scale (and ultimately patch-scale) may be compromised, because the flow of water and sediment which enables reaches to absorb, resist or recover from disturbance is compromised. Resilient river geomorphology is responsive to change and connected with the larger catchment. Catchment connectivity is thus a fundamental component underpinning resilience in river geomorphology.

Some river geomorphologies are naturally adjusted to high magnitude and frequency flood events. Monsoonal river systems have always experienced large floods and their resilience is unlikely to change in response to increased disturbance, in fact high magnitude floods have increased in recent decades (Kale et al. 1997) but without undue effects on river morphology (Macklin et al. 2012, Muhammad et al. 2013). Large lowland river systems have similarly been structured by large floods and are unlikely to show major geomorphological response to big floods in future (e.g. Croke et al. 2013). As such, these rivers can be construed as being resilient, even in an era of global change. However, Fryirs et al. (2015) suggest that while one such river (Lockyer Creek, which is typical of many southeast Queensland (Australia) systems in having a high flash flood index) appears to have been geomorphically resilient to large floods since European settlement (ca. 250 years), there remains a need for work to assess whether the resilience of such a system will continue in the same form, with increasing frequency of extreme floods projected with forecast climate change. Resilience in the past, does not necessarily ensure resilience in the future. The exact nature of changes in magnitude or frequency or both are likely to be critical in controlling future geomorphic trajectories. Fryirs (2013) calls for a better understanding of river sensitivity (aka resilience) by generating empirical data that can measure it, such as understanding the character and behaviour of a reach to assess the frequency and nature of adjustment, which is an approach to assessing geomorphic sensitivity outlined by Reid and Brierley (2015). The greatest challenge to understanding and forecasting resilience is the non-stationarity of river systems, and the nested hierarchy of sensitivity and resilience forces acting in a system in both space and time (Fryirs 2017) along with the length of record of change needed. Accordingly sensitivity / resilience of flood regimes to climate change is strongly contingent on specific environmental and historical context (Knox 2000, Phillips and Van Dyke 2016). Fundamentally, the concept of river geomorphology resilience and effective prediction of future resilience of river geomorphology must recognise the history of a river system. This contextualises both the present and future morphological structures and processes. Examination of river system response and recovery to past disturbance is a direct way of assessing resilience (Phillips 2009), and should be a priority to advance the understanding of the physical template of river habitat. Framing resilience of river geomorphology begins to meet these challenges, by advocating a consistency in defining principles of resilience thinking within the context of river science and management, and understanding how a geomorphologically resilient river behaves.

Conclusions

Resilience in river science recognises that geomorphologically resilient rivers may be highly dynamic, or exhibit classic stability (Figure 4). Resilience may be manifest in several ways, dependent upon the nature and frequency of disturbance and the sensitivity of the river system (Figure 1). Enhancing resilience may require an improvement of geomorphic sensitivity and propensity for change in the case of over-engineered rivers; or facilitating recovery following disturbance; or resistance to minimise disturbance in the first place. This depends on the nature of the system and its trajectory. River channel change is the norm (Raven et al. 2010) and this should be incorporated into understanding resilience. Ultimately, the least impacted by people and more connected the channel is with its floodplain and catchment, the more resilient it can be expected to be. Changing boundary conditions, like ensuring connectivity, will allow for changes to be worked through into a river which is both sensitive to and in equilibrium with the flux of water and sediment supplied by its catchment.

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Table 1: Key terms of resilience and geomorphology. Note: the terms are listed alphabetically and do not equate with one another. Key references in text.

Resilience	Definition	Geomorphology	Definition
Adaptability	The capacity of actors in a system to influence resilience (Walker et al. 2004)	Catastrophe theory	A mathematical theory that models the mechanisms of sudden and discontinuous change of state in very different types of phenomenon like river ecosystems. (Graf 1979)
Basin of attraction	The set of points defining the space of system. A state has been described in resilience thinking as the ball and cup model. The cup part of the model is envisaged as a 'state space' or 'basin' while the ball part of the model is defined by the variables that constitute the system for the problem of interest. (Thoms et al. 2017)	Equilibrium	There are many different types of equilibrium referred to in geomorphic systems and these are: *Static* equilibrium: where a balance of tendencies results in a static condition – a state of no change; *Stable* equilibrium: the tendency for a system to move back towards a previous equilibrium condition ie., to recover after being disturbed by external forces;

Unstable equilibrium: where small displacement leads to a greater change and usually achievement of a new stable equilibrium;

Metastable equilibrium: when stable equilibrium obtains only in the absence of a suitable trigger which carries the system state over a threshold into a new equilibrium regime.

Steady state equilibrium: where system properties are invariant to a given time scale but may oscillate around a mean state because of the presence of interacting variables;

Dynamic equilibrium: balanced fluctuations about a constantly changing system condition may have a trajectory of unrepeated states which overtime.

(e.g. Thorn and Welford 1994)

Connectedness	The internal controllability of a system, or the degree of connectedness between internal controlling variables and processes; connectedness reflects the degree of flexibility and rigidity of controls and the sensitivity of the system to perturbation (Holling 2001)	Relaxation time	The time taken by a system to adjust to a change in energy input (e.g. Howard 1982; Thoms et al. 2018)
Latitude	Changes in the character of the cup (Thoms et al. 2017)	System	A set of interrelated parts and are defined as having three basic components; elements, states and relations between elements and states (Thoms et al. 2018)
Resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (e.g. Walker et al. 2004)	Threshold	A threshold of landform stability can be exceeded either by intrinsic change of the landform itself or by change of an external variable. An *intrinsic* threshold implies changes can take place within a system without a change in an external variable. An *extrinsic* threshold describes change triggered by an external variable.

		(Schumm 1979)
Resistance	The difficulty to change within a basin of attraction or how difficult it is to move the ball around the cup (Thoms et al. 2018)	

Case Study 1: River trajectories of change and resilience: River Murray, Australia

A range of trajectories can be illustrated in the response of reaches along part of an 830 km section of the River Murray below the Darling junction (the lower Murray), in SE Australia. This reach of the River Murray (Figure Case Study 1 a) receives no major tributary flow. Flows are controlled mainly by large upland reservoirs (Jacobs, 1990), but along the lower Murray there are 10 low-level weirs constructed in 1922-35. The presence of these weirs has initiated a series of river channel adjustments (Thoms and Walker 1992) showing three basic responses:

1) Stabilizing river morphology (Locks 3-4, 8-10). After an initial period of fluctuation the cross section attained a new dynamic equilibrium, 30-40 years after closure of the weir, where it is 100-200 percent larger than the pre-regulation value. As such the alteration amplitude has exceeded resilience and this provides an illustration of meta-stable resilience (Figure Case Study 1 b). It is interesting to note the response of these weirs to a major flood in 1976 (peak 1078 $m^3 s^{-1}$). Cross sections below Locks 3 and 4 increased by 106 and 313 m^2 after the flood, but returned to pre-1976 values two years later. If these cross sections had not been in equilibrium with the regulated regime the pre-flood values may not have been returned to pre-flood values (as happened after a much larger flood in 1956). It is likely that the present cross-sectional areas will be maintained while the regulated regime persists.
2) Eroding river morphology (Locks 5-7). The first stage is similar to the stabilising response described above in that there is an initial period of fluctuation. Subsequently, erosion and enlargement of the channel have continued since the 1950s. As such the

reach is continuing to adjust, resistance exceeds recovery and resilience is dynamic (Figure Case Study 1 b).

3) Fluctuating or instability of river morphology (Locks 1-2). This response is distinctive because no clear pattern of adjustment is evident and the fluctuations appear to be independent of variations in discharge. There is some synchrony in changes in the cross-sectional area below Locks 1 and 2, and the magnitude of the changes is greatest below Lock 1, the furthest downstream weir. Here resistance could be construed as being equivalent to recovery, and resilience is in a steady-state (Figure Case Study 1 b, NB x-axis shows years).

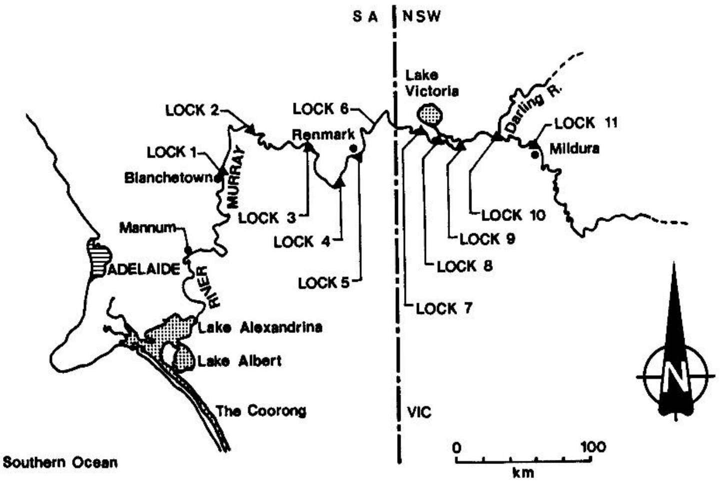


Figure Case Study 1 a. The Lower River Murray, South Australia. Flows in the River Murray, below its confluence with the Darling River, is regulated a series of 10 lock and weir systems.

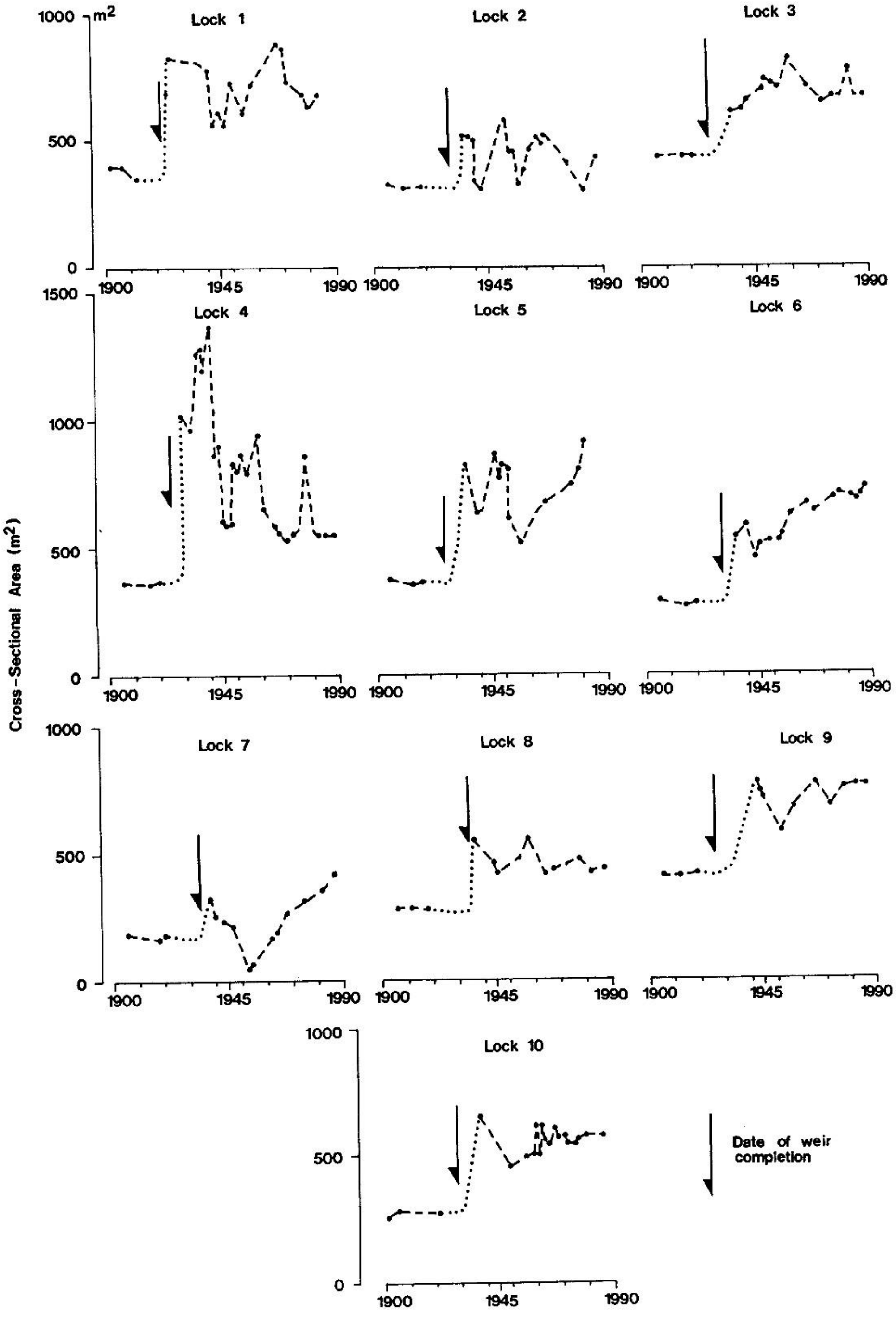


Figure Case Study 1 b. Trajectories of river channel behaviour downstream of 10 weirs (Locks 1-10) along the lower River Murray. Bankfull cross section areas are given (see Thoms and Walker, 1993)

Case Study 2: River management and resilience on the River Tay, Scotland

Research on the River Tay in Scotland (Gilvear and Winterbottom 1992) using old maps has shown how reach morphologies have been altered from moderately sinuous and active and wandering gravel bed ones to less sinuous and active channels with agricultural embankments on each side. During time periods lacking large floods the channel prevents inundation of the floodplain and allows farming. Thus during the 1970s and 1980s, flood events causing failures were in the order of one per decade. However, during large floods causing overtopping, such as ones in 1990 and 1993, multiple embankment failures occurred causing large scour holes and stripping of soil along the lines of relic channels (Gilvear et al. 1994). Gilvear and Black (1999) demonstrated that an upward shift in flood peaks of 5%, over the historical record dating back to the 1950s, could create an increase in embankment failures of up to 25%. Since 2000 a “flood-rich” period consistent with climate change predictions of flood magnitude and frequency have led to frequent flood embankment failures (in the order of every 3 years). Subsequently, costly human intervention is required to make the floodplain suitable for agriculture. The channel and floodplain morphology, under the embanked conditions, had very low resilience to the recent heightened flood peak regime and the current river management approach is effectively unsustainable. In reaches lacking embankments adjacent to the channel, it is noticeable how floods cause some minor channel morphological adjustment and inundate the floodplain, but with very little geomorphic consequence, such reaches are far more resilient to natural shifts in flood regime, and healthy river habitat is maintained. Since instability in some form is the norm in naturally adjusting, absorbing, resisting, recovering river systems, river management ought to take this into account (Newson and Large 2006). Failure to do so alters sediment dynamics and results in loss of habitat heterogeneity

(Downs et al. 2013, Edwards et al. 1999). There is thus a need in many engineered rivers to rehabilitate resilience, to allow for disturbance and recovery to disturbance, which is part of natural reach behaviour particularly in this flood-rich era that seems to be apparent globally (Thoms et al. 2018).

List of Figures

Figure 1. Bivariate composition of resilience defined. Resilience comprises both resistance to and recovery from disturbance. For example, a bedrock river will have a high resistance to change usually retaining its form regardless of the magnitude of a flood event. Highly engineered channels will also be resistant to flows for which they have been designed. In contrast a braided system is readily 'disturbed' by small events that reshape channels and bars. However, braided rivers have a high propensity for recovery from floods, retaining their form while not resisting change. When engineered channels are altered by floods that exceed their design capacity, they have a low recovery potential, similarly, a meandering channel that has been naturally straightened by cutoffs during a large flood will have a lower recovery potential (i.e. take longer) to recover its original sinuous form. What constitutes a resilient river is discussed later in this paper.

Figure 2. Resilience defined in a process-response system, which characterises geomorphic processes in river geomorphology. Resilience comprises resistance and recovery. Disturbance may produce no response (a), or a lagged response (b), or an immediate response (c), depending on the geomorphic sensitivity of the system (Phillips and Van Dyke 2016). An example of a lower system resilience threshold in the channel continuum conceptmight be straight (below the line) to meandering (above the line).

Figure 3. Resilience trajectories (a) steady state, (b) dynamic, (c) static, (d) meta-stable

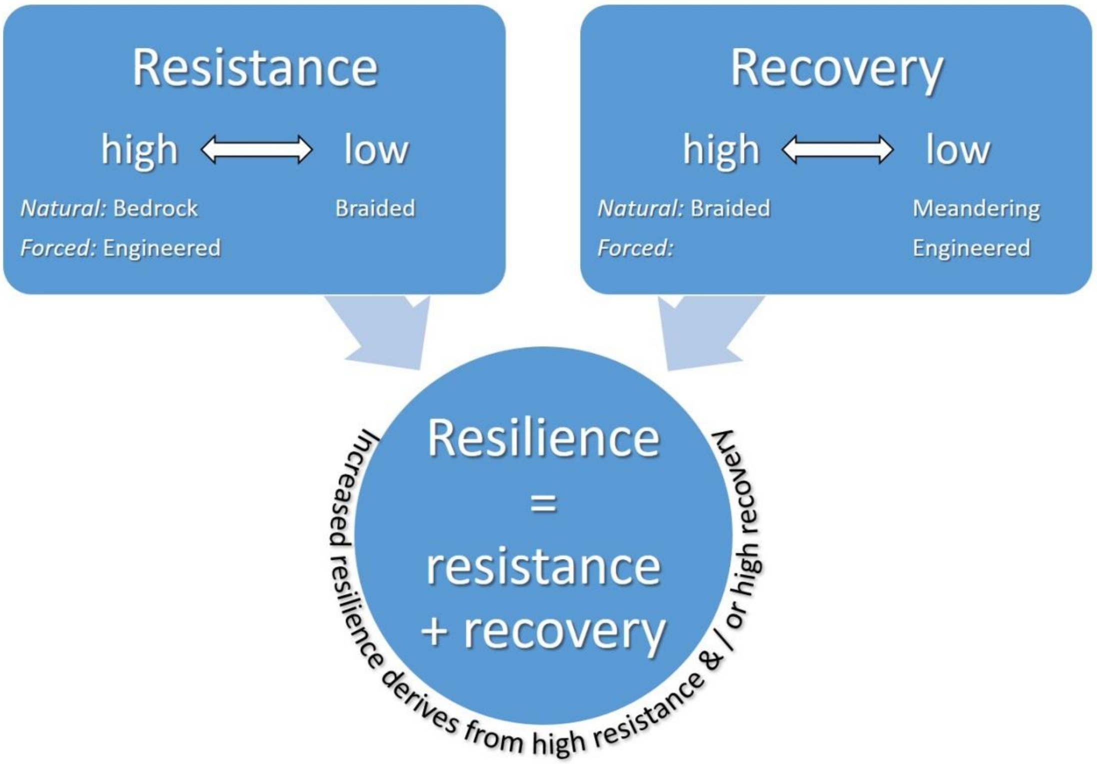
Figure 4. Resilience in amplitude, frequency and recovery space.

Figure 5. Aerial photo sequence of the lower Kiwitea Stream, near Feilding, New Zealand. A 100 yr flood in 2004 resulted in catastrophic widening of the river corridor, visible in the 2005 photography. Engineering has since modified the river corridor, but maintains sufficient width to accommodate large floods without resulting in the same large-scale changes of 2004. The red dashed line indicates the margin of the managed channel fairway. Image supplied courtesy of Peter Blackwood, Horizons Regional Council. Insert shows an oblique view of the channel transformation

and destruction of the approach to a State Highway bridge, located just to the far right (downstream) of the photo sequence. Note: the bridge remained intact and the pre-flood channel is clearly visible underneath it.

Figure 6. Transformation of a river in Haiti in response to Hurricane Matthew, October 2016. Flow is from top to bottom of the image.

Figure 7. Change in resilience with changes to disturbance events. Scenarios represented on the left of the diagram are typical of pulse disturbance, while a ramp disturbance is evident in scenarios on the right. The scenario of change in resistance to disturbance shows reducing resistance with each event and associated increase in response to ramp disturbance.



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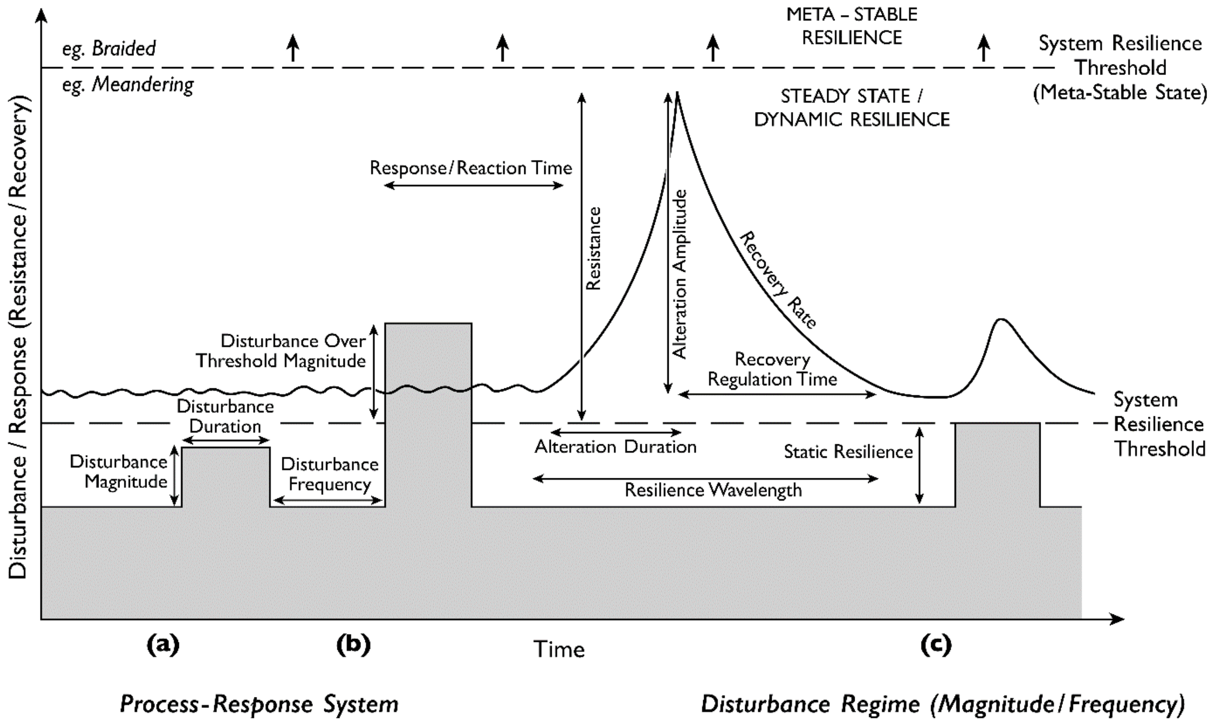

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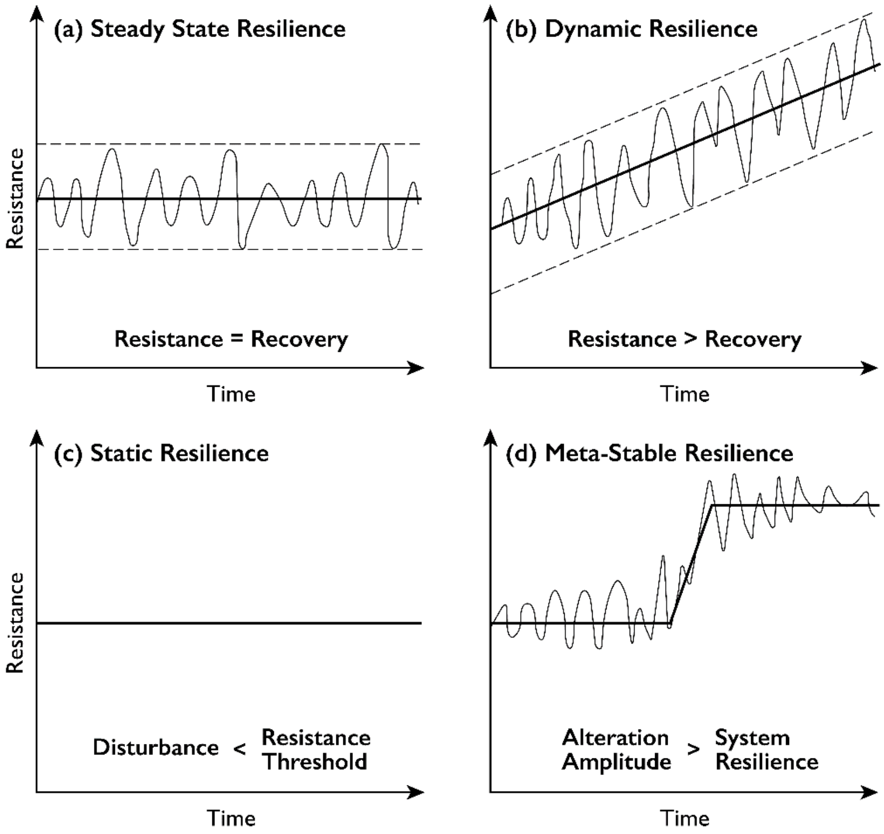

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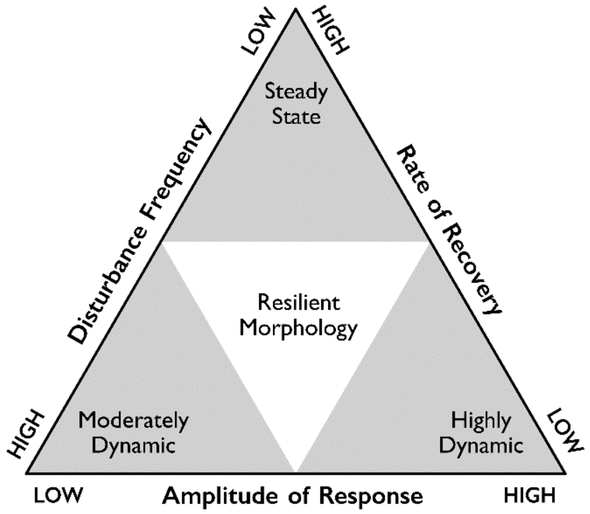

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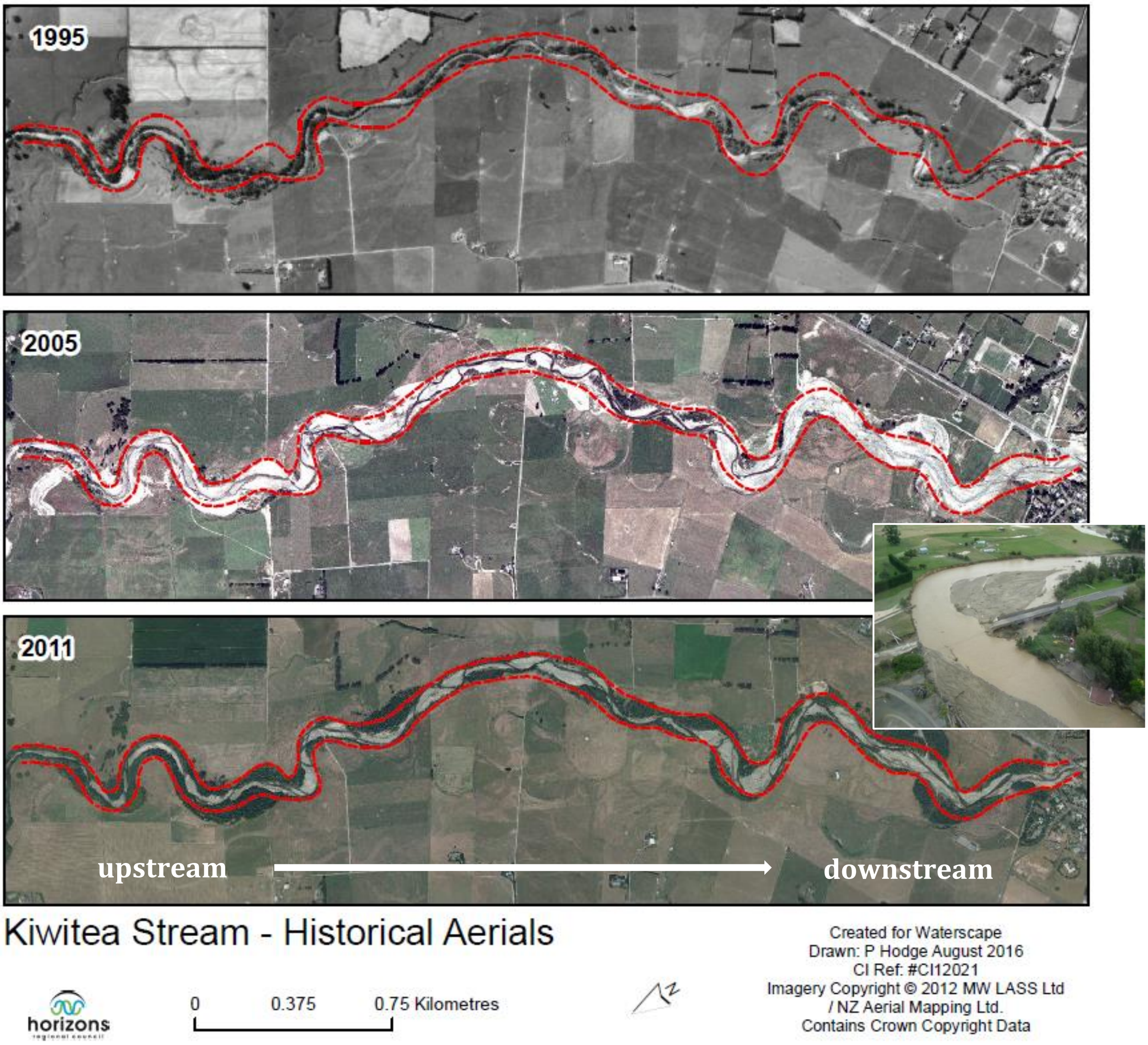

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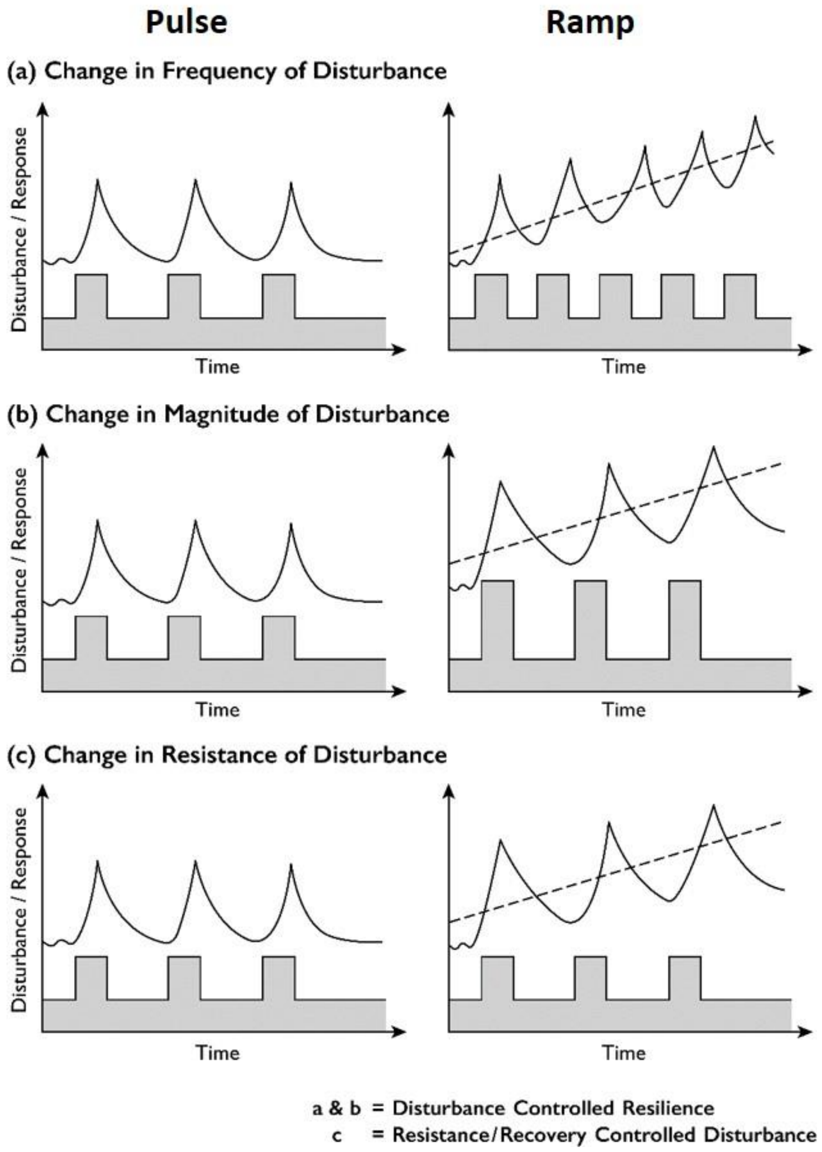

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