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Focus Article

Assessing the geomorphic recovery potential of rivers: forecasting future trajectories of adjustment for use in management

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In an era of river repair, the concept of recovery enhancement has become central to river management practice. However, until about the early 2000s there were no coherent geomorphic frameworks with which to forecast river recovery potential. While the practical uptake of such frameworks has been slow, and debates continue about what recovery means, some river management agencies in different parts of the world have applied related concepts within catchment scale, process-based approaches to river management. Agencies that make use of recovery enhancement approaches have reframed the way that vision setting, planning, and prioritization are undertaken. In this study, we review river recovery as a principle. We then present, using examples, an updated version of the framework for assessing river recovery and river recovery potential that is embedded in the River Styles framework. Finally, we show how the application of this framework can be used to better inform river management practice.

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INTRODUCTION

Notions of resilience have become extremely fashionable in recent decades. In scientific terms, the resilience concept refers to adjustments around an expected or characteristic condition which is often expressed in relation to an equilibrium state (e.g., Ref 1). Implicitly, these concepts suggest that if a system moves away from its expected or characteristic structure and function (range of process-form linkages), it will adjust back to that state through 'recovery' mechanisms. Although this is an attractive and powerful supposition, it can also be quite dangerous as it assumes that we know what these recovery states are, and we have appropriate understanding of the processes by which recovery comes about. Prospectively, misapplications of this principle may seek to impose notional stability in a world where change and evolution is the norm. Indeed, resilience notions now have distinctly political overtures in the quest for 'engineering resilience' and 'resilient communities' that are designed to help society adapt to (cope with) changes that are inevitable (e.g., Refs 2–7). Herein lies a key scientific dilemma: How do we make the most effective use of insights from the past to inform the future and how do we forecast future trajectories of adjustment? How do 're' words such as resilience, recovery, and restoration relate to contemporary 'buzzwords' which are used to represent contemporary and prospective future adjustments; concepts such as: emergence, complexity, contingency, nonlinear dynamics, thresholds, alternative stable states, no analogue states, novel ecosystems, uncertainty? In the management realm, how do notions such as recovery relate to the 'feral' world of rewilding,[8] and contested notions of wilderness, pristine worlds, and

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naturalness (cf. Refs 9 and 10)? Just as importantly, how do scientists and managers collaborate to make sense of these concepts and use them in real-world, on-the-ground applications where many rivers bear little relation to how they looked and functioned in the recent past (see Ref 11)?

Across much of the globe, flow regulation, river diversions, channelization, removal of wood and riparian vegetation, amongst many factors, have had significant geomorphological and ecological consequences. Few rivers retain their 'natural' geomorphic structure and function.[9,12–14] In many instances, changes to river morphology must be considered to be irreversible, in practical terms. Elsewhere, some rivers have proven to be relatively resilient to disturbance (e.g., Refs 15 and 16). In many settings, the long-term impact of human activities may be less evident at first view, as recurrent phases of disturbance can be masked by other attributes of the contemporary river system (e.g., Refs 13, 17–20). In tracing the evolutionary trajectories of river systems, it is clear that many rivers that have experienced multiple phases of deterioration have now started on a pathway toward recovery. So, what are the recovery prospects for rivers in different landscape settings across the globe? Recognizing the diversity of process–form interactions for different types of river, what does recovery look like (i.e., what would be expected in any given instance)? If the river was left alone, would its condition deteriorate or improve? Perhaps inevitably, these are deeply contextual (place-based, often highly contested) situations.[14,21]

The concept of river recovery has permeated the literature, particularly in ecology, for several decades (e.g., Refs 22–24). However, appreciation of geomorphic river recovery has been a much more recent phenomenon. Indeed, frameworks to assess geomorphic river recovery only came to fruition in the early 2000s (e.g., Refs 25 and 26). Concepts of geomorphic river recovery encapsulate how a river has adjusted in the past, and what that river is adjusting toward. In this sense, recovery is considered to be a natural process that reflects the self-healing capacity of river systems.[14,27] In an era of river repair,[28] in which process-based management strategies strive to 'work with nature,' critical understandings of the trajectory of river adjustment and change and the potential for river recovery are required.[29–32] Such analyses can support more sophisticated approaches to river management, such as 'space to move' and 'freedom rivers' initiatives where the river is allowed to freely adjust, such that a range of future scenarios may occur.[27,33–35]

However, river recovery rarely reflects an orderly, progressive, and systematic process of adjustment. The potential for river recovery following disturbance reflects a river's inherent sensitivity to change and the severity of impacts to which the system is (or has been) subjected.[36–39] Nonlinear dynamics and threshold-induced responses may make it difficult to determine the likelihood that any particular trajectory will be followed, when that will occur and at what rate.[40–42] As different parts of a system adjust at different rates, different reaches undergo transitions between different states over different timescales, driven by disturbing and forcing events that are often impossible to predict.[43] Multiple potential trajectories can emerge for any given river type dependent on the condition of each reach and its likely responses to future disturbance events, along with prevailing, system-specific driving factors and time lags.[44–47] Novel outcomes are likely and surprises are inevitable.[48,49] This presents countless challenges in framing adaptive approaches to management that embrace a commitment to experimentation alongside appropriate monitoring and documentation procedures.[50]

This study builds directly on the review of approaches to assessment of geomorphic river condition presented by Fryirs (Ref 51). Assessing geomorphic river recovery is 'the next step' in more sophisticated analyses of river systems that produce results that can be used to inform river management decision making.[29] We contend that 'emergent' geomorphic frameworks can apply recovery notions to provide critical understandings of the past (i.e., looking backward meaningfully) in efforts to inform the future in an effective, proactive, and precautionary manner. However, such analyses require examination of larger-scale pressures and limiting factors that influence prospects for river improvement. For example, land-use pressures and sediment fluxes in catchments must be understood with some degree of confidence (e.g., Refs 30, 52–57). Catchment-specific understandings of these relationships provide a critical information base with which to prioritize river reach interventions in a holistic manner.[58] Such efforts seek to maximize cumulative benefits while minimizing off-site impacts of interventions.[59] Proactively framed, precautionary catchment action plans can be used to justify expenditure as part of a recovery enhancement approach to river management, wherein likely future scenarios are forecast and monitored under a range of likely conditions (e.g., climate/water, land-use/vegetation, or sediment) to aid risk assessment and planning.[56,60]

In this study, we review geomorphic river recovery as a principle. We contend that clear definitions and conceptual frameworks are required to inform scientific investigations of river recovery, and that these should be used consistently to communicate and scope management practices (cf. Ref 61). We also propose that contextual (spatial and temporal) approaches to analysis be theoretically sound to ensure that systematic, place-based applications can be used with confidence to inform management applications. With this in mind, the aims of this study are:

1. To outline a generic set of concepts and procedures to assess geomorphic recovery and recovery potential. Using examples, we present an updated version to assess river recovery and river recovery potential that is embedded in the River Styles framework.[29]
2. Show how the application of these procedures can, and has, been used to better inform river management practice using examples from Australia.
3. Provide a set of guiding principles that should be considered in all geomorphically informed river management applications.

DEFINING RIVER RECOVERY AND RECOVERY POTENTIAL

Few frameworks have successfully recognized the need to separate *classification procedures* which merely group like-with-like,[29,30,62] from *condition assessments* which compare disturbed reaches with reference condition reaches for particular river types and interpret the drivers of change,[51,63] and *recovery assessments* that place each reach in a catchment context and forecast future trajectories of adjustment.[29,55,56,64] Analyzing river recovery requires a solid understanding of river character, behavior and condition, and how this has changed over space and time.[29] A scaffolded set of catchment-specific information bases is required before assessments of river recovery can be made with some level of confidence.

When analyzing river recovery, a separation is made between defining the *past*, and *current* trajectory of adjustment, and then using this to determine the *potential* of the reach to recover. The former can be determined using historical and evolutionary analysis, while the latter is a forecasting or scenario-building exercise.[55,56,60] In this context, *river recovery* is defined as the trajectory of change toward an improved geomorphic condition.[29] However, river recovery is not simply the reverse of river degradation. River systems may evolve in unpredictable ways, and the emergence of novel ecosystems is likely in some instances.[46,49] Therefore there is no re-, and unfortunately 'covery' is not a word! Hence, river recovery is part of rehabilitation practice, it is *not* restoration.[14,31,65,66] There is no such thing as restoration of an evolving ecosystem. By extension, *river recovery potential* is defined as the capacity for improvement in geomorphic condition over the next 50–100 years.[29] This requires that forecasting and scenario building be undertaken. To achieve this, each reach must be analyzed in its catchment context, assessing the impact of pressures and limiting factors (through pattern and connectivity analysis) on the likely future trajectory/trajectories of adjustment.[46,55,56,58] River recovery potential tends to be assessed for time frames of 50–100 years, so that the analyses can provide an assessment of what is realistically achievable in management practice and for vision development (c.f. Ref 60).

HOW DO YOU ANALYZE RIVER RECOVERY AND RECOVERY POTENTIAL? CONSTRUCTION OF A 'RIVER RECOVERY DIAGRAM' AND RECOVERY POTENTIAL MAPS

Different types of river operate under particular sets of boundary conditions. As any given river type has a distinctive character and behavior, natural recovery processes may relate specifically to that type of river, though broader generalizations can often be drawn. Assessments of underlying causes and mechanisms of adjustment build on catchment-scale analyses of river character, behavior, and downstream patterns. These considerations, alongside evolutionary analyses of river adjustment, flow/sediment connectivity relationships, and condition assessments for the system of interest are outlined by Brierley and Fryirs[29,31]) and Fryirs.[51]

The route by which a reach has attained its present geomorphic condition has a significant impact on its future trajectory of adjustment.[9,41,42,55] Therefore, understanding river evolution and past geomorphic change provides a means to explain the timing, rate, and magnitude of adjustment that has occurred and why the river is in the state (condition) it currently is.[51] These analyses provide foundation insights (the 'starting point') with which to forecast likely future scenarios (and trajectories).[42,56,58,67–69] Catchment-specific, geomorphic guidance on such matters provides a platform with which to consider what is physically achievable in rehabilitation efforts for any given system.[14,30,66]

River Recovery and Evolutionary Trajectory

To assess river recovery requires that the history, pathway, and rate of adjustment of each reach in the catchment of interest is known. While this may appear to be an exhausting, resource-rich, and time-consuming exercise, field-based geomorphic insight coupled with historical air photographs, maps or other resources, and ergodic reasoning can be used to assess significant 'timeslices' in the evolution of river systems, thereby providing sufficient information with which to start such investigations.[68,70–72] Fryirs et al.[68] present a worked example showing multiple evolutionary timeslices representing differing stages of geomorphic adjustment, and associated changes to geomorphic river condition.

Evolutionary analyses enable responses to natural or human disturbances to be framed in terms of the long-term pattern and rate of changes that reflect the capacity for adjustment for any given type of river.[55,67,68] If possible, such analyses should assess and interpret threshold conditions under which river adjustment and change occurred. From this, the *trajectory* of adjustment can be appraised by placing each evolutionary timeslice onto a '*river recovery diagram*' (Figure 1).[25,29,64,73]

In the River Styles framework,[29] three main trajectories (or pathways) of adjustment are determined, namely: degradation, restoration, and creation. These trajectories encompass a minimum of five key states of adjustment, namely: intact, degraded, turning point, restored, and created conditions. Depending on the circumstances, these diagrams can be as simple or as complex as required. In some applications of this framework, multiple degradation, restoration, and recovery trajectories are depicted (see section below for one example).

Appraisals of river recovery entail analysis of adjustments away from an initial or baseline state, conceptualized on Figure 1 as an 'intact' condition, but this can be adapted to suit analytical needs as a particular state in the history of a given river; e.g., river adjustments post dam construction, or where human disturbance has been occurring for hundreds or thousands of years. It is a decision of the user to determine what initial state and timeslice is represented at this position on the diagram, and this should be stated explicitly at the start of the process. In many settings it is useful to provide a sense of what the river was like prior to disturbance so the user has a sense of how much (or little) the river has changed and what some of the core characteristics of the river are. This intact or initial condition is not intended to represent a 'reference condition' or 'target condition' for condition assessment or river rehabilitation (see Ref 55).

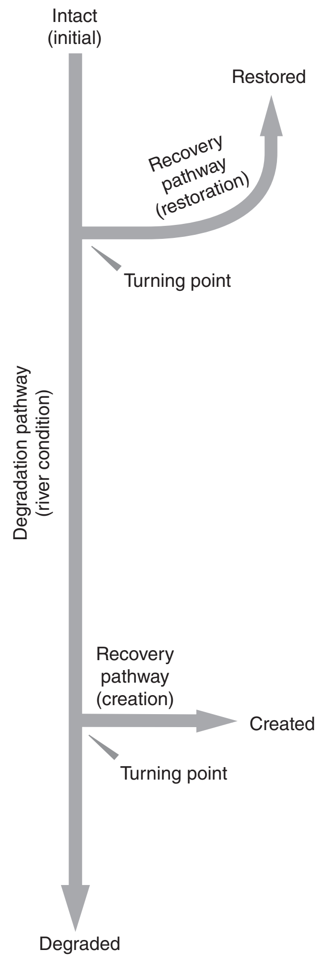
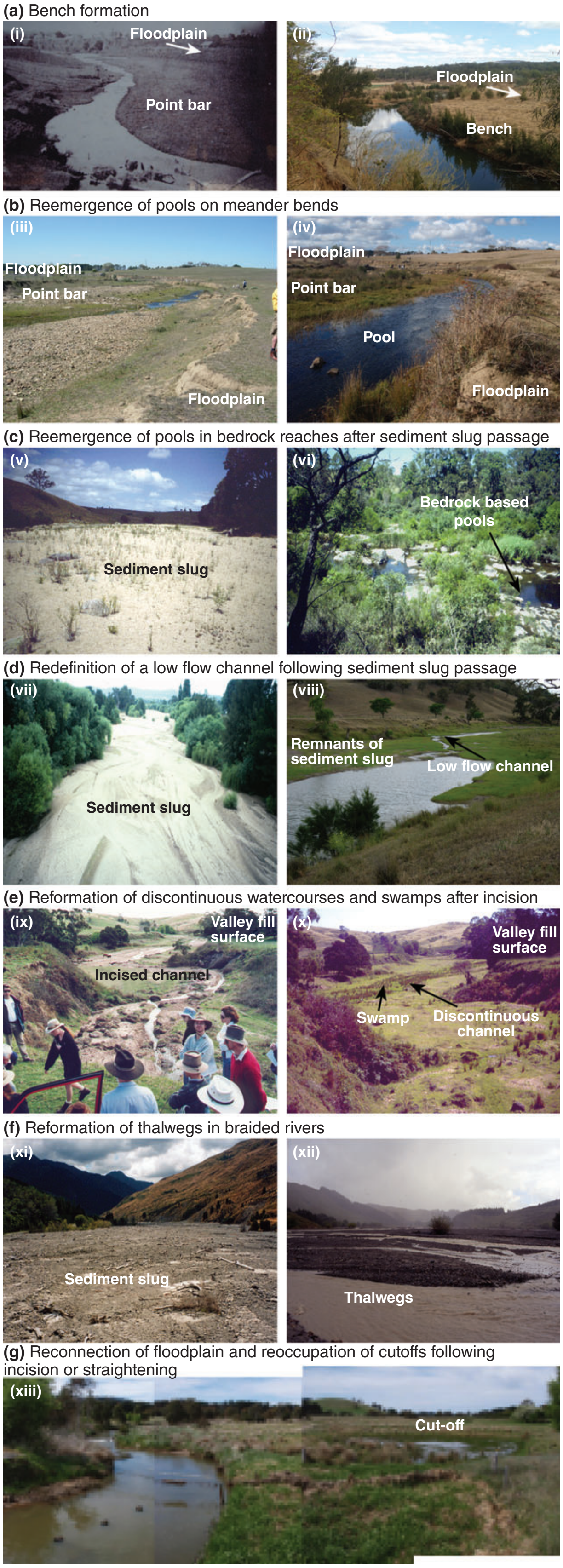


FIGURE 1 | Components of the river recovery diagram. [Reprinted with permission from Ref 29. Copyright 2005 Blackwell Publications]

The vertical line on the left hand side of the *river recovery diagram* conveys a continuum of degradation away from this baseline (*intact or initial*) condition. Degradation in this context is defined as a deterioration in geomorphic condition. If the geomorphic character and behavior of the reach are not significantly different from an initial state, the reach is considered to be intact. As conveyed here, the vertical 'degradation pathway' is progressive (i.e., linear). Depending on the degree/extent of degradation, the contemporary reach may sit some distance from this intact state. Barely perceptible adjustments will see the reach positioned close to the intact state, whereas more impacted (*degraded*) instances are plotted further down the vertical axis. If the reach has been altered, and is experiencing progressive deterioration in its geomorphic condition, specific



indicators of degradation or modified rates of geomorphic adjustment may be detected. For example, the range of geomorphic units is often inappropriate for the river type and anomalous processes (or rates of processes) are occurring. For example, sand sheets that have infilled pools or cover the floodplain indicate that there is an oversupply of sediment to that reach.[26] Essentially, the vertical axis of the river recovery diagram conveys a gradation of geomorphic river condition from good to poor.[29,51]

The extent to which a river has moved away from an intact condition (i.e., become more degraded) exerts a major influence upon prospects for 'what is achievable' once recovery begins. One of the key challenges in analysis of river recovery is detection of the transition point at which a river moves from its degradation pathway to its recovery trajectory, which is shown on the right hand side of Figure 1. We refer to this transition stage as a 'turning point.'[29] Depending on the type of river under consideration, differing geomorphic units (i.e., landforms[74]) can be considered to represent 'landforms of recovery.' Examples are shown on Figure 2. Deposition of bench deposits at channel margins narrow enlarged (incised and widened channels (Figure 2(a)). In some instances, these features may create 'inset floodplains.' In instances where a channel has been over-widened, the return of bed features such as pool-riffle sequences indicate the recovery of bed heterogeneity relative to the homogenous plane-bed (sand sheet) conditions of the degraded system (Figure 2(b)). Similarly, the reemergence of pools, or the redefinition of a low flow channel (thalweg) may occur in reaches where a sediment slug has passed

FIGURE 2 | Forms of river recovery as indicated by the presence, absence, or assemblage of geomorphic units in a reach of different river types: (a) bench formation and channel narrowing along a fine-grained meandering river (i) Lockyer Creek, Queensland in the 1890s and in (ii) 2014; (b) reemergence of pools along a meandering gravel bed river (iii) Mulloon Creek, NSW in the mid-2000s and in (iv) 2015; (c) reemergence of pools in a bedrock controlled river after the passage of a sediment slug (v) Sandy Creek, Bega Catchment, NSW and (vi) Bemboka River, Bega Catchment, NSW; (d) redefinition of a low flow channel (thalwegs) following the passage of a sediment slug along a low sinuosity sand or gravel bed river (vii) Bega River, NSW and (viii) Pages River, Hunter Catchment, NSW; (e) reformation of discontinuous watercourses and swamps after incision of a valley fill swamp (ix) Wolumla Creek, Bega Catchment, NSW in 1998 and in (x) 2009; (f) reformation of thalwegs in braided rivers following the passage of a sediment slug (xi, xii) Waipaoa Catchment, New Zealand; and (g) reconnection of floodplains and cutoffs along a meandering fine-grained river (xiii) Wingecaribee River, NSW. Photos: (i) © Queensland State Library, (ii–xii) K. Fryirs.

(Figure 2(c) and (d)). Elsewhere, for quite different (cut and fill) types of river, reformation of swampy (wetland) conditions on the bed of an incised channel within valley fill deposits marks a return to discontinuous watercourses (i.e., recovery is underway) (Figure 2(e)). If a braided river has been degraded such that channel multiplicity has been greatly reduced, regeneration of mid-channel bars and reoccupation or reformation of former thalweg channels would be considered as recovery processes (Figure 2 (f)). For active meandering rivers, cut-off channels or even avulsed channels may be landforms of recovery (Figure 2(g)). For many alluvial rivers, reconnection of floodplains (hydrologically) and reactivation of features and their formative processes can be considered as part of recovery. In many instances, mutual biotic–geomorphic interactions provide insights into assessments of river condition and associated processes of geomorphic recovery. Vegetative measures are often, but not always, tightly linked to geomorphic recovery; management of exotic (weed) invasions is an example of an exception to this premise. Analysis of the assemblage of geomorphic units within a reach provides a key *diagnostic indicator* of whether recovery is underway.[29]

Caution is required when assessing geomorphic indicators of river recovery, as similar features may represent either degradation or recovery depending on the type of river under investigation, and its context. The same principle is applied for assessment of geomorphic river condition.[51] For example, the presence of step-like inset features within a macrochannel can represent either degradation or recovery (Figure 3). If these features are identified as ledges (Figure 3(b), (d), and (f)), channel expansion is underway and the river is likely in a degraded state (see Ref 72). If they are identified as benches (Figure 3(a), (c), and (e)) then channel contraction is underway and these units are acting to narrow previously enlarged channels (see Ref 72). In the latter

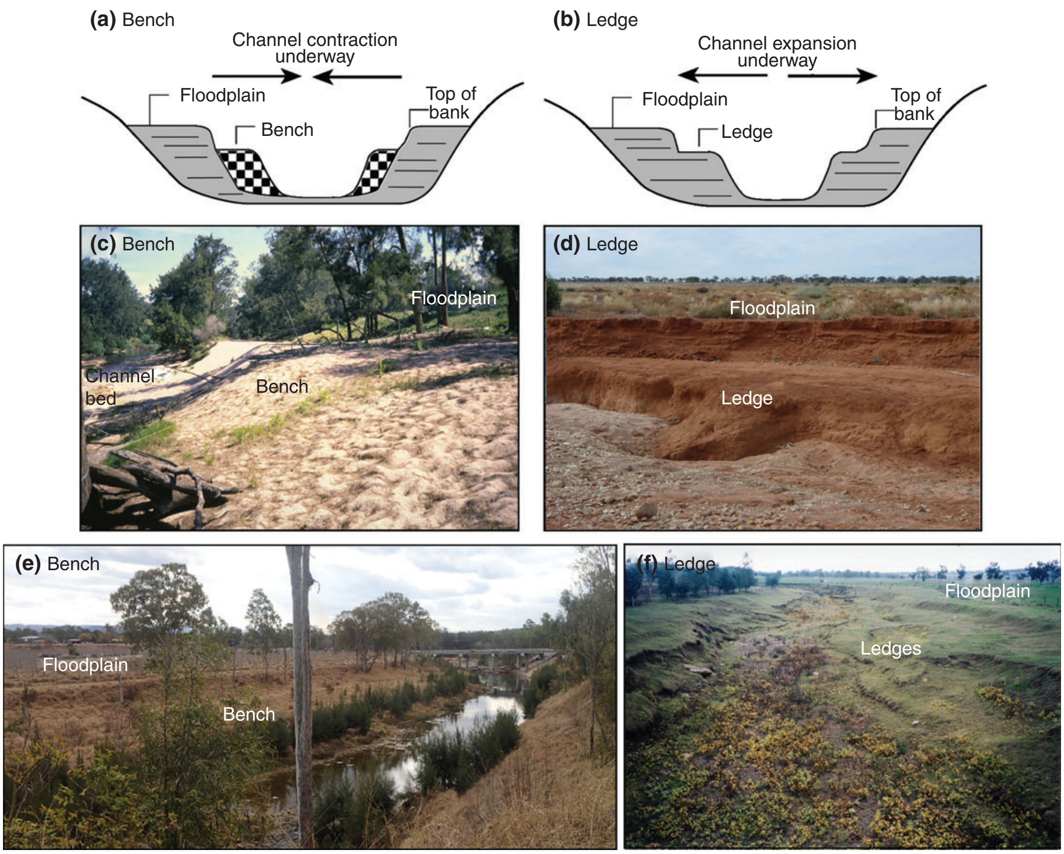


FIGURE 3 | Benches and ledges as indicators of channel contraction (recovery) and expansion (degradation) respectively. Benches are step-like depositional landforms that are attached to channel banks. They have a different sedimentary structure to the adjacent floodplain (a) and tend to occur where channel contraction is underway after channel widening. They are key indicators of river recovery. Ledges are step-like erosional features along channel banks. They have the same sedimentary structure to the adjacent floodplain (b) and occur where channel expansion is underway. They are key indicators of river degradation. (c) Macdonald River, NSW, (d) Polpah Creek, Western NSW, (e) Lockyer Creek, Queensland, (f) Lachlan River, NSW. All photos: K. Fryirs.

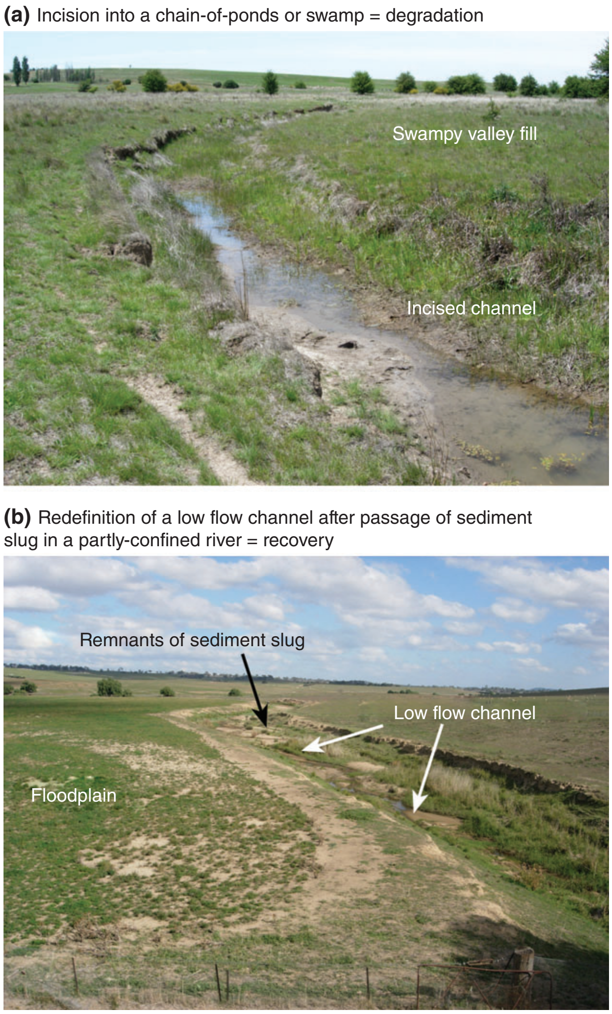


FIGURE 4 | Reading the landscape to inform interpretations of river degradation and/or recovery. Although the same type of process may be occurring, the interpretation of whether degradation or recovery is underway is river type dependent. (a) Incision and channel formation in a chain-of-ponds system is a degradation process, whereas (b) redefinition of a low flow channel after the passage of a sediment slug in a low sinuosity sand bed river is considered a recovery process. Photos: (a) Mulwaree Ponds, NSW, (b) Fish River, NSW. All photos: K. Fryirs.

instance, mechanisms of geomorphic recovery are underway. Similarly, low flow channel realignment and definition could indicate degradation (e.g., where incision has been triggered; Figure 4(a)) or recovery (e.g., where flow paths become better defined in a sediment slug affected reach; Figure 4(b)) (e.g., Ref 45). As noted earlier, reaches that show initial signs of recovery are considered to be at the turning point.

The transition to recovery can occur at any stage along the sliding scale of the degradation pathway. The turning point marks a period in time where a bifurcation in the reach's evolution is possible, reflecting a transition toward either restoration or creation, or continued degradation. The pathways of adjustment depicted on the right hand side of Figure 1 differentiate between a *restoration* and a *creation* trajectory.

Restoration in this context is used to describe the reinstatement or emergence of characteristics (and processes) in the system that occurred at some stage in the past and are represented in the intact or initial state. This reflects the expected capacity for adjustment of the type of river under consideration. Once on this trajectory, the river is showing signs that an improvement in geomorphic condition is occurring. Restoration does not mean a return to predisturbance conditions as this is impossible in evolving systems where boundary conditions have been altered. This is why this trajectory is offset to the right of the diagram and this process is not represented as simply a return along the sliding scale of degradation at the left.

Creation is defined as recovery toward a new, alternative condition that did not exist previously at the site. The river is adjusting toward a best attainable state given the prevailing boundary conditions (which have often been altered). Creation in this context is used to describe the emergence of characteristics (and processes) in the system that have not occurred in the past and are 'new' to this reach. Once on this trajectory, the river is showing signs that an improvement in geomorphic condition is occurring.

The recovery trajectory adopted is dependent on the history of change (i.e., whether (ir)reversible geomorphic change has occurred), present reach condition, and prevailing flux boundary conditions. Ultimately, improvements in geomorphic condition along both the restoration and creation pathways reflect the operation of self-healing processes. The further down the degradation scale a reach sits, the less likely it is that it will head along the restoration trajectory, and creation is the most likely future scenario.

Determination of 'what is achievable' for any given reach, whether it is on a degradation, restoration, or creation trajectory, reflects whether the reach has been subjected to reversible or irreversible adjustments (i.e., whether the reach continues to operate as the same type of river with the same character and behavior (but a range of geomorphic condition), or whether change to a different type of river has occurred; see Ref 29, 51, and 75). Reaches that have experienced *reversible* geomorphic change have the potential to recover along the restoration pathway. These reaches are generally in good or moderate geomorphic condition and sit higher on the degradation pathway. An example may be a river reach that has experienced the passage of a sediment slug and characteristics of the preslug river are returning (e.g., reemergence of pools; Ref 26).

However, if flux boundary conditions have been severely altered, creation is underway. These reaches tend to be in poor geomorphic condition and sit low on the degradation pathway. Creation can occur for the preexisting river type or more commonly a new river type that has a different behavioral regime (i.e., *irreversible river change* has occurred; see Refs 25, 42, and 68). An example may be where a preexisting river type is transformed through urbanization and active rehabilitation is artificially recreating previous geomorphic structures. More commonly, however, reaches that have experienced irreversible geomorphic change (and changed river type) are unable to recover along the restoration pathway.[75] In these cases the recovery diagram becomes more complicated and a new degradation pathway needs to be added to depict this change (see section below). An example may be where human disturbance has irreversibly changed the river type through channelization from a meandering river to a low sinuosity river, but river condition is improving for the new low sinuosity river type that previously did not exist at that location.

In many instances, the extent of response to disturbance exerts a primary control upon whether a reach has followed a restoration pathway (or will do so in the future). Often this reflects whether geomorphic adjustments have been reversible (where restoration is possible) or irreversible, where creation is the only option. Restoration is underway when the reach shows signs of reinstating structure and function that previously occurred along the reach, and geomorphic condition is improving. For example, the reinstigation of swamps and discontinuous watercourses are indicative of geomorphic recovery along cut-and-fill rivers.[76] However, the further down the degradation scale a reach sits, the less likely it is that a reach will recover along a restoration pathway. Reaches in moderate or poor condition that have experienced reversible geomorphic change can recover along either the restoration or creation trajectory.

Creation is the only recovery pathway in those reaches that have experienced irreversible geomorphic change. Restoration is no longer a viable option, as it is not possible to reinstate previous character and behavior of these reaches. In these cases, reaches are only able to recover toward the best attainable condition for the contemporary river type. Once irreversible geomorphic change has induced a shift to a different river type, the reach now displays geomorphic process–form interactions that were not previously experienced at any stage in the evolutionary sequence. To show this on the river recovery diagram, a solid line is placed across the degradation pathway of the recovery diagram and a new ‘arm’ developed. In assessment of ‘moving targets’ for management actions,[42] the future range of options available for river degradation or recovery can be significant. Layers of complexity can be added to the river recovery diagram to depict the range of prospective river futures. Building on these conceptualizations, five examples of river recovery diagrams are shown in Figure 5.

Example 1 on Figure 5 is an intact river. The reach sits at the top of the degradation pathway. As yet, no notable deterioration in geomorphic condition has occurred, and the river continues to adjust within its expected capacity for adjustment (i.e., the behavioral regime of the river is unaltered). The Thurra River in East Gippsland, Australia, is a well-documented example of this type of adjustment.[77] A wide range of examples exist, many of which are found in National Parks and conservation areas around the world. Under these conditions, only *minimal* rehabilitation intervention is required as the river retains a good geomorphic condition. In the River Styles framework, a high priority is placed on these *conservation* reaches.[29,75]

Example 2 on Figure 5 demonstrates an instance where disturbance (whether natural or human-induced) has instigated deterioration away from an intact condition. The reach continues to operate as the same type of river, with the same character and behavior (i.e., irreversible change has not occurred). Some elements of the structure and function of the river, or the extent/rate of process interactions, have been modified, so the reach has moved down the degradation pathway, away from the intact condition, impacting on the geomorphic condition of the reach. The River Murray in Australia exemplifies this type of adjustment. Since European settlement in the early 1800s, geomorphic river condition has progressively deteriorated.[78] Another well-documented example is the Tagliamento River in Italy where a well-functioning braided river remains in place (despite mining and other disturbances occurring over time) and river recovery is underway.[54–56] In terms of rehabilitation, *minimalist or low* intervention strategies are required to induce recovery. In the River Styles framework, it is recommended that the optimal approach to management builds out from remnant reaches of river that are in good condition.[29] Rivers displaying this progressive form of adjustment are considered *high-moderate* priorities in

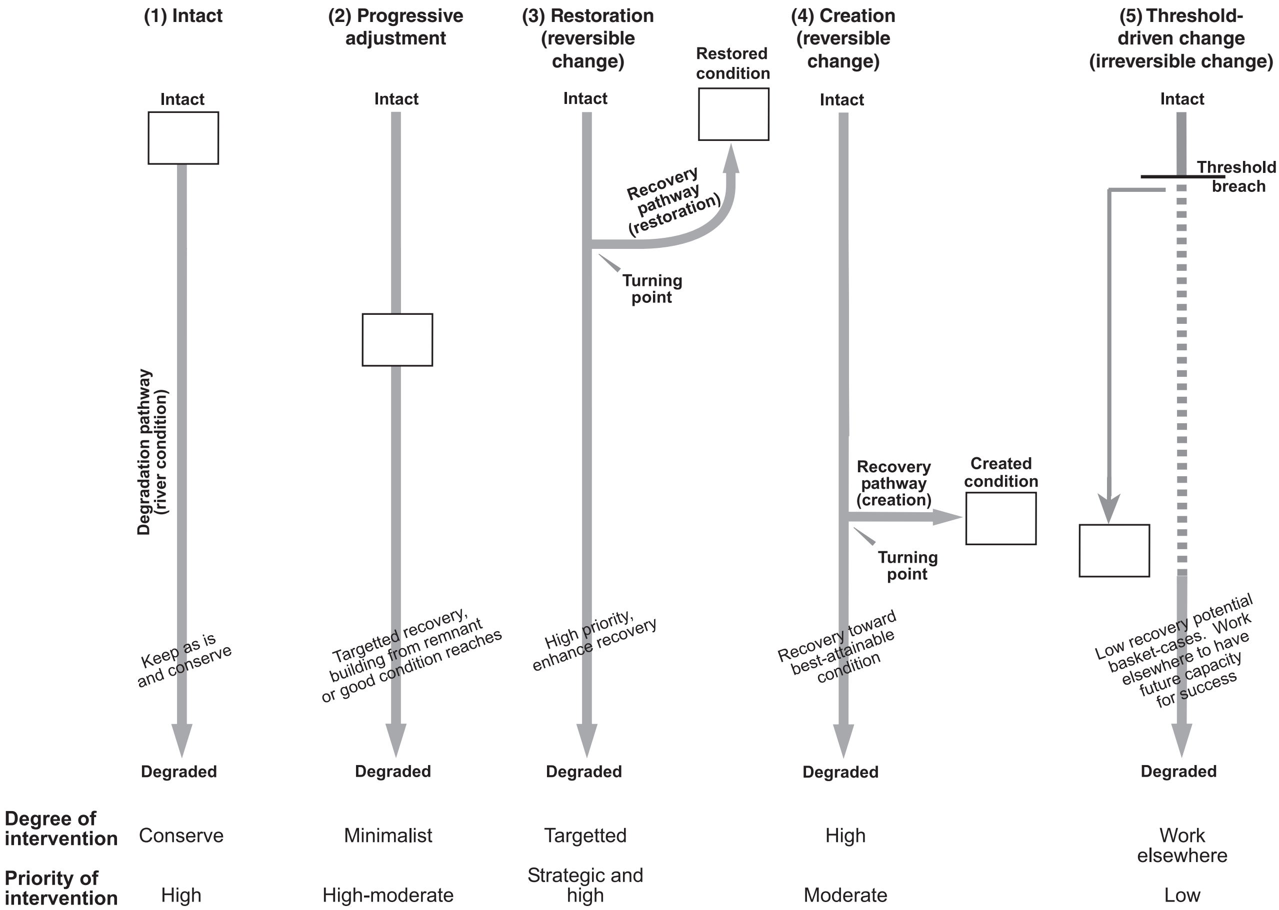


FIGURE 5 | Simple examples of river evolution diagram. Boxes represent position of reach described in the text. [Reprinted with permission from Ref 75. Copyright 2008 Island Press]

river management plans, as there are significant prospects for substantive responses to carefully targeted interventions.[75]

Example 3 on Figure 5 demonstrates an instance where recovery has commenced for a reach that has not deviated very far from an intact condition. Moves toward recovery along the restoration pathway may occur naturally or they may be enhanced by human intervention. In this instance, the reach has started to regain some elements of its former physical structure and function that had previously been lost. River change has not occurred. Rather, improvements to geomorphic river condition are evident. Management can enhance these recovery tendencies. For example, installation of wood structures and replanting of riparian vegetation actively enhanced the natural recovery of the Never Never River, a wandering gravel bed river in the Bellinger catchment, Australia.[79] Similar outcomes have occurred along various low sinuosity gravel bed rivers in Utah, USA[80,81] where minimal intervention and passive rehabilitation associated with adjustments to vegetation and beaver dam installation have occurred. These examples show how working within a recovery enhancement framework can engender very effective outcomes. To maximize prospects for success, the reach should be in relatively good condition (i.e., it sits high on the degradation pathway), such that is it only necessary to enhance rather than reinstigate natural recovery processes. In context of catchment-based river management plans, these rivers require *minimal* and *targeted* intervention, as they are considered to be *strategic* and/or *high recovery potential* priorities in which passive restoration activities may bring about relatively quick, effective responses (e.g., Refs 75, 80, and 82).

The fourth example on Figure 5 represents a reach that has experienced a deterioration in condition, but not to the extent that river change has occurred. The river is showing signs of recovery. However, given the poor condition of the reach, and its position low on the degradation pathway, prospects for recovery along a restoration pathway are limited. Rather, the trajectory of change in this instance is along the creation pathway, and recovery prospects are limited to the best-attainable structure and function for this river type. Examples of this type of recovery can occur along urban and regulated rivers. For example, many Councils in Sydney, Australia are rehabilitating severely degraded rivers by reinstating artificial pool, riffle and wetland structures along rivers that have maintained a partly confined configuration.[83] In many places in Europe, multichanneled, braided, and wandering networks have been transformed into single-thread meandering streams as a result of river regulation and river training. While these systems show signs of recovery, this is occurring for the single-channel variants rather than the multichanneled variants.[58] In these cases, the ultimate aim is to reinstate some 'natural' geomorphic (and ecological) function to the current river, improving its condition. These situations often require costly, *high* intervention river rehabilitation strategies, with *moderate* prospects for improvements to ecosystem condition.[75]

The fifth example on Figure 5 represents reaches where disturbance has brought about threshold-induced adjustments to river character and behavior such that the river now operates as a different river type (i.e., irreversible change has occurred) and no recovery is underway. This reach sits at a low position on the degradation pathway. A new degradation pathway is added to the diagram to note the change in river type and associated change in trajectory. Well-documented examples of this type of adjustment have been documented from the Bega catchment, Australia.[84–86] Since European settlement in the 1860s, major changes to geomorphic structure and function have limited prospects for river recovery, constraining what is achievable in river management terms. Elsewhere these types of examples have been described as 'basket-cases' with low recovery potential.[29,87,88] Within the catchment-based river management strategy proposed as part of the River Styles framework, these rivers require *high* levels of intervention and are given *low priority*.[29] In these instances, it is likely that management interventions will be more efficient and cost-effective when applied elsewhere in the catchment, striving to enhance prospects that off -site impacts from *working elsewhere* may, over time, shift this river toward a higher recovery potential state.[75]

These examples show how relatively simple representations of evolutionary adjustments and trajectories can provide a useful set of information to assess recovery prospects. To date, there are few instances where these principles have been fully applied at the catchment scale, assessing how reach-reach interactions influence the potential for recovery (see next section). Catchment-scale analyses can be used to show different reaches of the same type of river at different stages of adjustment. From this, space for time analyses (ergodic reasoning) can be applied to predict likely future states for a given reach. Fryirs et al.[68] present a detailed example of these principles from Wollombi Brook, NSW, Australia. In this catchment, there are two main variants of partly confined river (meandering and a low sinuosity planform-controlled variant). Different reaches of these river styles have experienced various stages of evolutionary adjustment, and currently display different condition. Evolutionary analysis, ergodic reasoning, and geomorphic condition analysis have been used to depict the cross sections displayed in Figure 6.[68] Some reaches have shifted river style from the meandering variant to the low sinuosity variant and are now considered to be irreversibly altered. These reaches now operate on the left of the diagram with a new set of trajectories. Reaches that have maintained a meandering planform occur on the right of the diagram. Sections (c), (i), (j), and (b) currently occur in the catchment and sections (e) and (k) are forecasts. Building on these principles, Brierley and Fryirs[42] outline the range of prospective future states, from which they derive 'moving targets' for management actions. Critically, in conducting such analyses, it is reach-to-reach interactions that determine the recovery potential of rivers in different parts of the catchment.

River Recovery Potential

The recovery diagram shown in Figures 5 and 6 provides a reach-based tool with which to assess and communicate the trajectory of geomorphic adjustment of a river. In scoping the potential for future adjustments, however, such reach-based summaries must be placed in their catchment context to appraise how changes to flux boundary conditions are likely to impact upon process–form interactions in any given reach. In other words, these catchment scale conditions determine the *potential* for river recovery, wherein catchment-specific *pressures* and *limiting factors* may inhibit (or enhance) river recovery.[29,30,55,58,89] Pressures refer to human-induced practices. They can be either internal or external to the catchment. Examples include land-use (vegetation cover) change, water and sediment management policies (e.g., flow regulation, dam construction or removal, sand/gravel extraction, and dredging), climate change, and so on. Limiting factors are internal

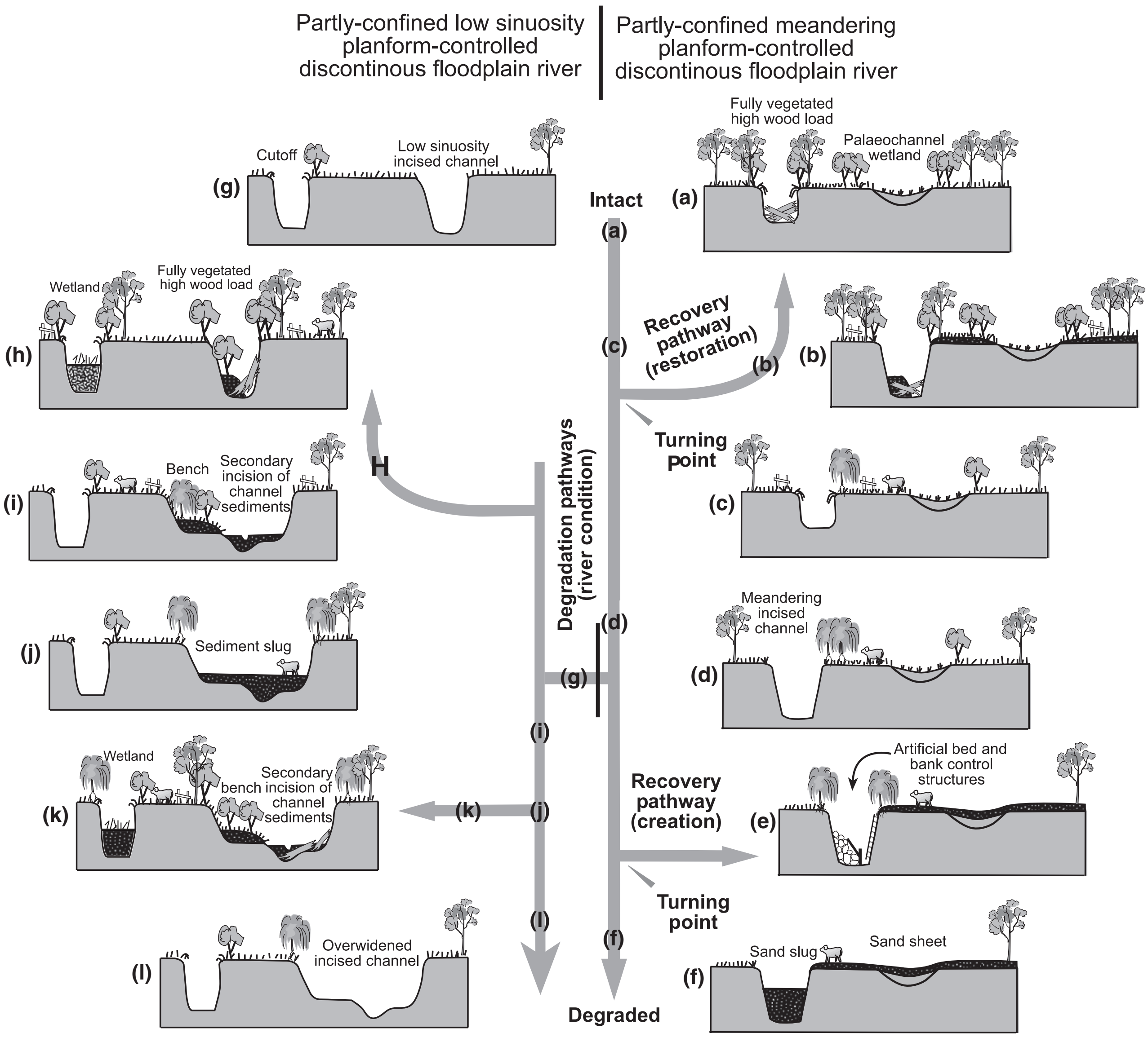


FIGURE 6 | More complex river recovery diagram for reaches of partly confined river in Wollombi Brook, NSW, Australia. Based on information in Refs 42 and 68.

to a particular catchment. Physical considerations such as sediment availability and transport capacities, discharge and flow management considerations, and vegetation distribution, character, and composition exert a direct influence upon the potential of a reach to move along a recovery trajectory.

In different parts of the world, sediment availability in catchments, and the position of the reach under consideration, influence recovery potential in different ways. In the New World and Old World, the time frame of human disturbance and landscape response can span hundreds or thousands of years, significantly influencing the intensity, extent, and timing of landscape response, and therefore the potential for recovery and the time frame of recovery.[90,91] The availability of sediment for river recovery, and hence the time frame of recovery, may vary markedly in differing landscape settings such as tectonically active, capacity-limited landscape relative to passive tectonic, transport-limited landscapes.[52,92] In sediment starved or exhausted landscapes, particularly those where colonial land-use practices have accelerated sediment supply and delivery, the time frames for river recovery may be in the order of hundreds or thousands of years (essentially unrealistic over management time frames) (e.g., Refs 64, 77, 84, and 93). In other places, legacy sediments produced by landscape disturbance associated with intensive

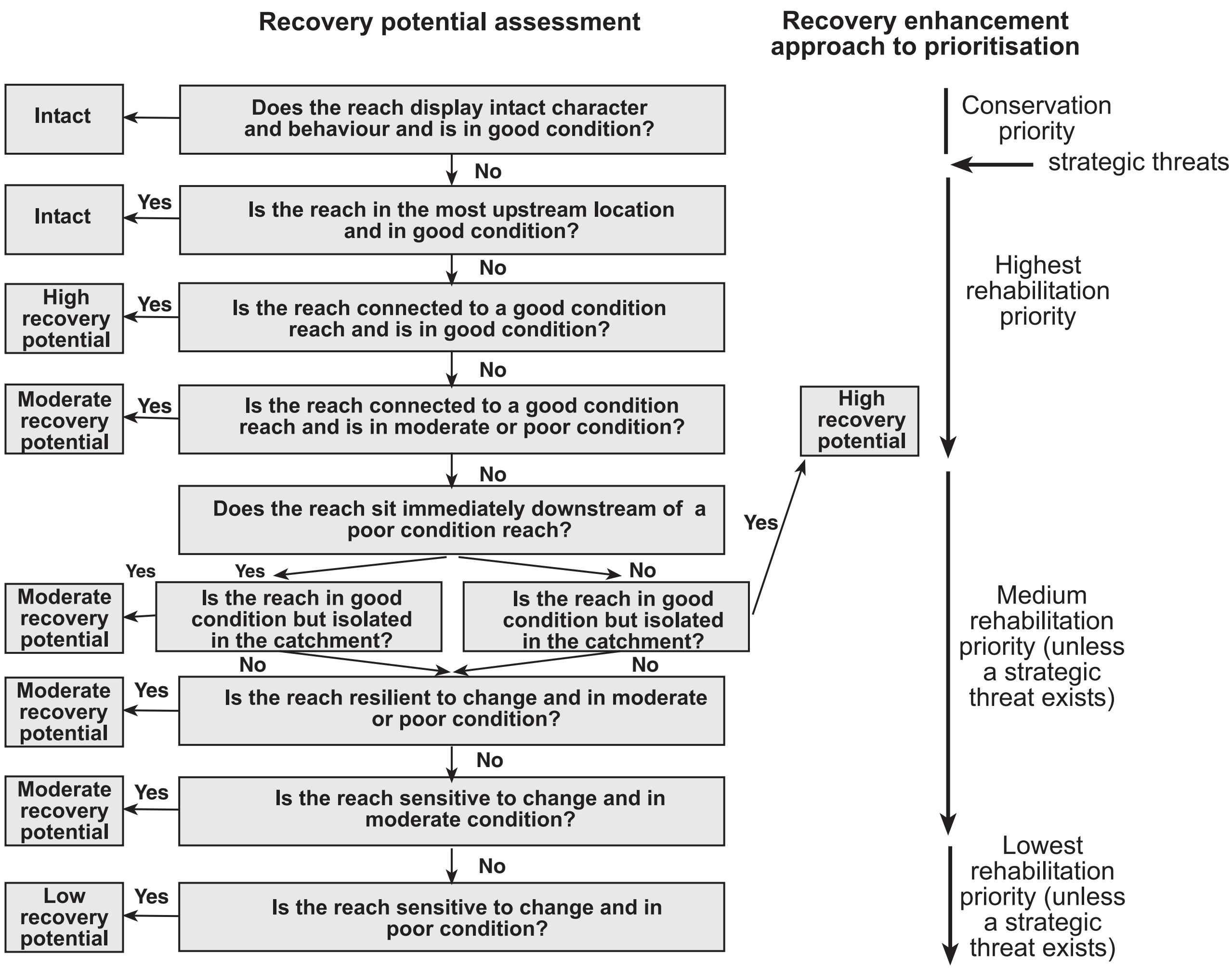


FIGURE 7 | Decision making tree for assessing the recovery potential of a reach and the associated prioritization as part of a conservation first recovery enhancement approach to river management. [Modified from Ref 29]

agriculture or industries may be key to river recovery (or not).[13,94–97] Dams and reservoirs have severely disrupted sediment conveyance along many rivers, severely limiting prospects for river recovery.[91,98] Dam removal typically results in rapid reworking of stored sediments and pulsed sediment flux (e.g., Refs 99–102). Meaningful interpretation of *context* is key to such analyses with river recovery potential being assessed in relation to system-specific boundary conditions, including, i.e., pressures and limiting factors. This then allows managers to assess in which reaches sediment should be 'locked up' and stored for river recovery, and where sediments can be released (see Ref 64).

By examining the pressures and limiting factors that regulate system functioning over time, inhibitors to system recovery can be removed or targeted for remediation.[55,89,103–105] The severity of the impact and the degree to which physical function is compromised or impaired will dictate the potential for that system to resist the forces of change and show signs of recovery (or maintain the status quo), thereby impacting on prospects to improve river condition.[29,46,51,63,106,107] In some cases, systems recover quickly once an inhibitor is removed, demonstrating remarkable resilience and capacity to 'bounce back' (e.g., Refs 19 and 89). In other instances, especially if intrinsic or extrinsic thresholds have been breached, the system may have little capacity to 'bounce back.'[46]

Analyses of river recovery potential assess how pressures and limiting factors affect different types of rivers at different positions in a catchment, and how these various responses are (dis)connected and interact.[52,53,58,64,108] Quantification and monitoring of patterns and rates of physical fluxes (sediment, flow,

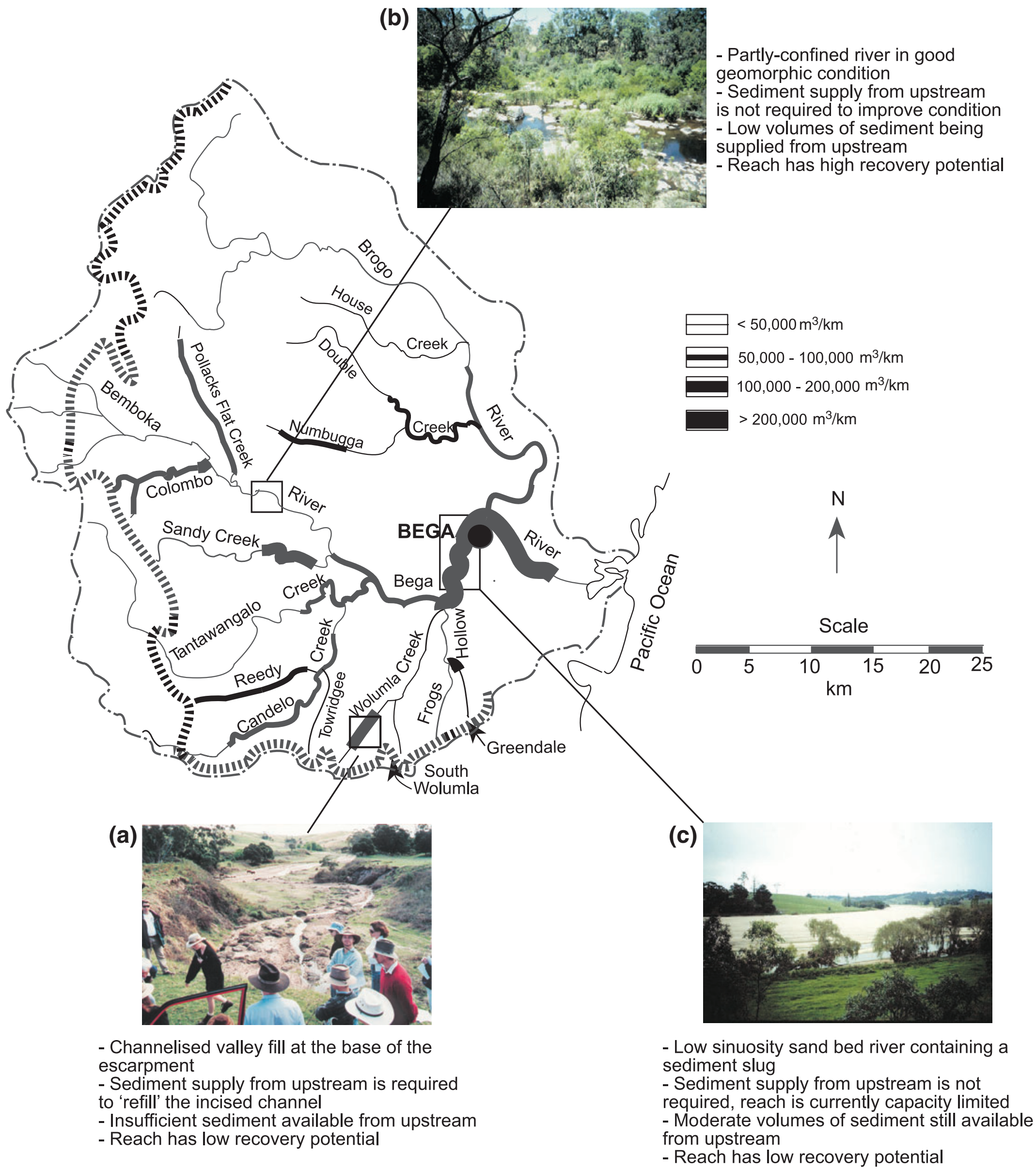


FIGURE 8 | An example of how a catchment-scale sediment budget and associated analysis of (dis)connectivity can be used to assess river recovery potential. This example is for the Bega catchment, NSW, Australia. The thickness of the streamline segment represents the volume of sediment stores in the in-channel zone. As sediments in these stores are readily transported, they are available for reworking and supply to downstream reaches. Some reaches (e.g., a) require sediment from upstream to recover. Other reaches do not require sediment from upstream because they are either in good condition (e.g., b) or are already oversupplied (e.g., c). The (dis)connectivity of sediment supply drives these interactions and assessments of recovery potential. Figure from Ref 39 reproduced with permission, © John Wiley and Sons. Sediment sources basemap sourced from Ref 64 Photos from K. Fryirs.

and vegetation associations) build upon understandings of the strength of linkages and (dis)connectivity that determine the propagation of disturbance responses through a system.[45] For example, analysis of the position of river reaches relative to blockages (buffers, barriers, and blankets; see Refs 52 and 53), and the operation of 'switches' that impact upon catchment-scale fluxes, can be used to forecast, for a range of different scenarios, whether (1) disturbance will be manifest, (2) whether this is 'helpful' or 'unhelpful' in terms of enhancing, suppressing or disturbing recovery along for any given reach, and (3) whether there will be any lagged responses that need to be considered in the future.[46,89,108] Integration of these various forms of information is required to determine the relative time frame over which this

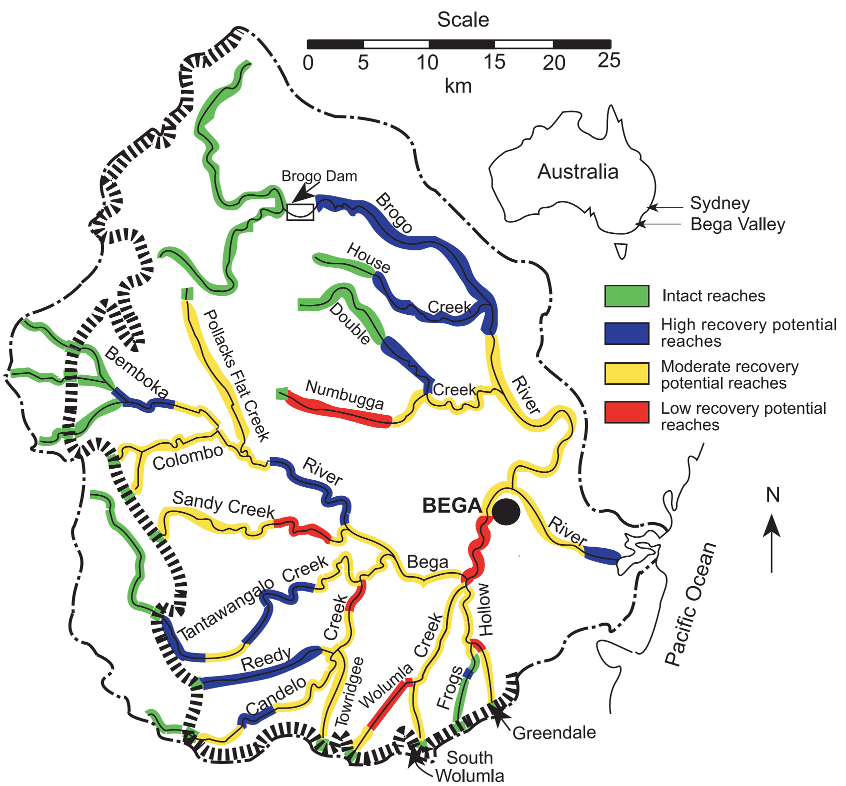


FIGURE 9 | Example of a catchment-based river recovery potential map for Bega catchment, South Coast, NSW Australia. [Reprinted with permission from Ref 29. Copyright 2005 Blackwell Publications; Ref 73, Copyright 2005 John Wiley & Sons]

may occur. Process-based modeling applications can be used to support these investigations.[56,109–112] Before process-based modeling applications can be meaningfully applied, it is important to conceptualize catchment-scale process relationships and prospects (potential) for recovery for all reaches in a catchment.

Brierley and Fryirs[29] provide a generic decision making tree that encapsulates analyses of river condition and resilience, reach position and connectivity to assess river recovery potential (Figure 7). Figure 8 demonstrates how this approach has been applied in the Bega Catchment, NSW, Australia.[25,39,64] In this system, sediment supply is the primary limiting factor to geomorphic river recovery. However, the distribution of available sediment stores is highly variable, and this availability and the (dis)connectivity relationships in this system drive recovery prospects (Figure 8).[25,29,64,73] In this example, a channelized fill reach occurs in the upstream parts of the catchment (Figure 8(a)). The recovery potential of this reach is dependent on there being significant sediment supply from upstream to trigger an improvement in geomorphic condition (i.e., reduce channel capacity, mainly through bench formation). In this case, however, sediment supply from upstream is insufficient to produce benches and the desired contraction processes over management time frames of 50–100 years. This reach has low recovery potential. Elsewhere in the catchment, a partly confined river type is operating as expected and is in good geomorphic condition (Figure 8(b)). In this case, a supply of sediment from upstream is not needed to improve condition or maintain the integrity of the reach. The sediment budget tells us that sediment supply from upstream is relatively minor and therefore the recovery potential of this reach is high. In the most downstream reaches of this catchment, a sediment slug occurs and the reach is transport capacity limited (Figure 8(c)). The reach is in poor geomorphic condition and its recovery potential is low.

When this approach is applied across a catchment, river recovery potential maps can be produced that provide the evidence-base for management decision making and prioritization (e.g., Figure 9). In a conservation first, recovery potential based approach to river rehabilitation, reaches that have high recovery potential and therefore show signs of recovery are considered the highest priorities for action and/or investment (see, e.g., Refs 29, 81, and 113).

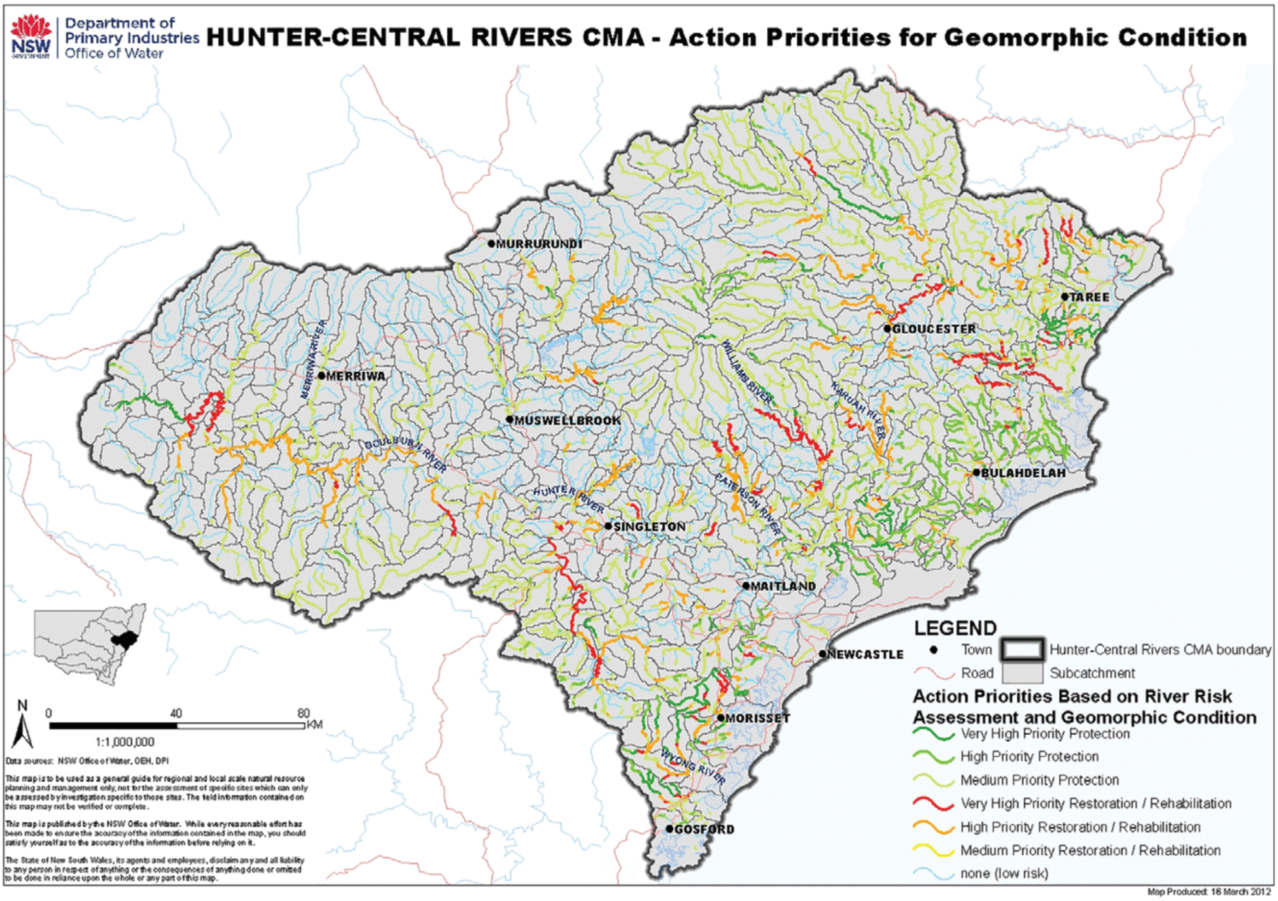


FIGURE 10 | Example of a geomorphology action priority plan based on assessment of geomorphic river condition and recovery potential using the River Styles framework. This example is for the entire Hunter Valley, a 22,000 km^2 catchment on the central coast of NSW. This type of work has now been completed across NSW for regional river management planning and assessment. Image: © NSW Department of Primary Industries (Office of Water) and reproduced with permission.

USING ANALYSES OF GEOMORPHIC RIVER RECOVERY AND RECOVERY POTENTIAL IN RIVER MANAGEMENT

In an era of river repair, recovery enhancement approaches have been used to guide river conservation and rehabilitation in some parts of the world for a decade or more.[14,18,25,31,54–56,58,64,73,87–129] In these places, such principles and approaches are meaningfully incorporated with river management and decision-making processes, supporting catchment-scale vision setting, planning, and prioritization.[11,116] In other places, momentum is building for adoption of such practices (e.g., Refs 118–120). Appropriate information bases to support such place-based decision making are a fundamental part of this process. In addition to standard analyses of river character and behavior (forms and processes) expressed through classification of river types, fully interrogated layers of information on river condition (see Ref 51) and recovery potential[58,63,64,73] are required. When rolled out across large areas (e.g., Figure 10), these procedures provide a basis to support regional- or national-scale river management programmes, enabling generation of insights into comparability (representativeness) and transferability of different forms of management intervention. This provides an important part of the management toolkit to evaluate developments in policy and resource planning.[29,30,58,114,115] Cost:benefit analysis and risk assessment can support this process (e.g., Refs 35, 115, 121, and 122). When placed in a spatial and temporal context, assessments of river recovery potential provide the baseline set of information for determining 'windows of opportunity for recovery' (c.f. Ref 123), allowing decisions to be made about *whether* river management is required, *where* and *when* to intervene and when to *opt-out* of management because the system is self-healing without intervention (e.g., Figure 11) (cf. Refs 51 and 124). Importantly,

FIGURE 11 | Examples of where river recovery has been enhanced by management intervention, then an opt-out strategy to allow the river to self-heal. (a) Recovery of a meandering gravel bed river; the Gloucester River, NSW. (i) In the late 1990s T-jacks were installed along an overwidened channel with an eroding concave bank. These structures 'float' and are designed to trap sediment and induce bench formation. Riparian replanting accompanied this strategy. Management agencies opted-out of further work. By 2015 (same view) (ii) the reach is largely unrecognizable. The channel has contracted, a range of geomorphic units has reformed or emerged (i.e., pools) and riparian vegetation has recovered. Management of exotic species is the only form of ongoing maintenance. Photos: (i) K. Fryirs, (ii) F. Hancock, NSW DPI. (b) Recovery of a wandering gravel bed river; Pappinbarra and Bellinger Catchments, northern NSW. (iii) Many wandering gravel bed rivers in the Pappinbarra Catchment are highly degraded with sediment slugs clogging channels and artificial channels being cut through them. (iv) Installation of wood structures and replanting of riparian and instream corridors along the Never Never River, Bellinger Catchment in the late 1990s and early 2000s has resulted in the reinstatement of a multiple-channel network with significant geomorphic and ecological integrity. This is Example 3 used in Figure 5. Photos: (iii–iv) K. Fryirs.

these sophisticated, carefully scaffolded datasets also provide scientific rationale for monitoring programmes that meaningfully target what we seek to address through management interventions.[50,125–129]

In summary, analyses of river recovery and recovery potential can be used to provide invaluable datasets and toolkits for river management. These tools can be used for:

1. Determining the limiting factors or pressures on river recovery and whether these pose 'threats' to the recovery potential of a system. Targetted, strategic initiatives that tackle the most serious issues may be required to 'trigger' recovery processes. Catalytic actions may support such interventions.
2. Determining which evolutionary trajectories are more likely for a range of different flow, sediment, and vegetation scenarios, and placing confidence limits or probabilities on the likelihood of river recovery for any given river in any given system.
3. Setting stepping stones and targets for conservation and rehabilitation, framing long-term catchment framed visions in relation to ranges of options that capture likely future variability in river forms and processes (i.e., moving away from linear thinking and single target states).
4. Providing a basis for the recovery-enhancement approach to prioritization, prioritizing reaches with high recovery potential as little intervention will likely produce positive effects elsewhere. Over time, this may shift reaches with low recovery potential toward moderate recovery potential.

5. Selecting measures that must be taken to achieve a given outcome, building upon assessment of the likelihood that this outcome can be achieved and sustained, and the prospective cost:benefit and risk:consequence of doing so.
6. Providing the basis for determining 'when to leave it alone' (passive restoration) versus when to intervene, and where in a catchment activities are likely to be most successful and achieve 'best bang for buck.' The level of recovery potential can be used as a surrogate for the level of expected intervention required to improve condition, aiding decision making on when to opt-out of management because the system is in a state of self-healing without intervention.
7. Determining at what scale intervention is required. For example, will local reach-scale intervention (e.g., dam removal) be sufficient, or is catchment-scale intervention on pressures and limiting factors (e.g., sediment supply) required to adjust (dis)connectivity patterns and impacts.
8. Determining whether management activities in certain parts of catchments can be used to accelerate form-process activity to enhance recovery, and where certain measures may have negative off-site impacts that will damage the recovery process.
9. Providing an evidence-based framework for processes of river repair, working within an ecosystem-based approach to river conservation and rehabilitation.

CONCLUSION

In this study, we have reviewed river recovery as a principle and have presented a framework for assessing river recovery and river recovery potential using the River Styles framework. We have shown how the application of this framework can be used to better inform river management practice.

Care needs to be taken when using notions of resilience and recovery in an emergent, changing, and evolving world. Effective steps forward build upon careful definition of these concepts and clear articulation (and documentation) of steps taken to assess and measure related attributes/processes. In prompting meaningful uptake of these notions, and their uptake to management, it is important to contextualize and integrate these concepts as part of coherent, broadly framed management toolkits. Also, these place-based (catchment-specific) applications need to be related to broadly based regional and theoretical framings as part of adaptive learning exercises, giving careful consideration to the transferability of understandings for differing management applications. Even in light of best available understanding, it may be wise to 'expect the unexpected,' framing future prospects as ranges of options (or moving targets) and ensure that these are effectively communicated to scientists, managers and the community as part of proactive, strategic, and realistic river management practice.

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