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A STREAM EVOLUTION MODEL INTEGRATING HABITAT AND ECOSYSTEM BENEFITS

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ABSTRACT

For decades, Channel Evolution Models have provided useful templates for understanding morphological responses to disturbance associated with lowering base level, channelization or alterations to the flow and/or sediment regimes. In this paper, two well-established Channel Evolution Models are revisited and updated in light of recent research and practical experience. The proposed Stream Evolution Model includes a precursor stage, which recognizes that streams may naturally be multi-threaded prior to disturbance, and represents stream evolution as a cyclical, rather than linear, phenomenon, recognizing an *evolutionary cycle* within which streams advance through the common sequence, skip some stages entirely, recover to a previous stage or even repeat parts of the evolutionary cycle.

The hydrologic, hydraulic, morphological and vegetative attributes of the stream during each evolutionary stage provide varying ranges and qualities of habitat and ecosystem benefits. The authors' personal experience was combined with information gleaned from recent literature to construct a fluvial habitat scoring scheme that distinguishes the relative, and substantial differences in, ecological values of different evolutionary stages. Consideration of the links between stream evolution and ecosystem services leads to improved understanding of the ecological status of contemporary, managed rivers compared with their historical, unmanaged counterparts. The potential utility of the Stream Evolution Model, with its interpretation of habitat and ecosystem benefits includes improved river management decision making with respect to future capital investment not only in aquatic, riparian and floodplain conservation and restoration but also in interventions intended to promote species recovery. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: Stream Evolution Model (SEM); channel evolution; freshwater ecology; habitat; conservation; river management; restoration; climate resilience

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INTRODUCTION

It is now generally accepted that river engineering and management that works with rather than against natural processes is more likely to attain and sustain the multi-functional goals (e.g. land drainage, flood risk management, fisheries, conservation, biodiversity, and recreation) demanded by local stakeholders and society more widely (Wohl *et al*., 2005; Thorne *et al*., 2010). This, coupled with growing recognition that the range and value of ecosystem services provided by rivers increase with the degree to which they are allowed to function naturally, fuels the drive for restoration of fluvial systems degraded by past management and engineering actions that have proven, in the long term, to be unsustainable (Palmer *et al*., 2005).

However, complete restoration of a river to some former condition is seldom possible, nor always desirable (Downs and Gregory, 2004), and deciding whether partial restoration, rehabilitation or environmental enhancement is the best way to treat a damaged stream raises fundamental questions for river managers responsible for achieving increased biodiversity or the protection and recovery of endangered species. Specifically, serious questions arise concerning the nature of the pre-disturbance condition to which a given river should be restored, the likely sequence (and habitat impacts) of channel adjustments associated with post-project evolution and the merits of restoring the river to some former condition rather than facilitating, or even enhancing, its progression to a configuration that is, first, better adjusted to the prevailing hydrological and sediment regimes and, second, more resilient to the unavoidable impacts of future climate change and/or land use.

In this paper, these questions are addressed by

1. revisiting well-established Channel Evolution Models (CEMs) for streams that respond to disturbance through incision,
2. updating these CEMs in light of recent research, including that on pre-disturbance channel forms in Europe and North America, to propose a more broadly based Stream Evolution Model (SEM),
3. linking the evolutionary stages of stream adjustment to indicators of habitat and lotic ecosystem benefits and

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4. considering how the SEM linked to ecosystem benefits might be used to better understand, strategically manage and sustainably restore freshwater aquatic systems.

Channel evolution models help us conceptualize how single-thread alluvial channels may respond to disturbances, through a series of morphological adjustments, which can be generalized into an evolutionary sequence common to streams in different physiographic settings. On this basis, past evolutionary changes can be explained and future ones predicted through *space-for-time* substitution within the affected fluvial system. The utility of CEMs (originating from Schumm *et al*., 1984; Simon and Hupp, 1986) to inform interventions for managing the impacts of channel instability endures, and subsequent authors have expanded the concept (e.g. Doyle and Shields, 2000; Simon and Darby, 2002; Beechie *et al*., 2008; Hawley *et al*., 2011). In contrast, there has been little application and even less evaluation of CEMs in the contexts of aquatic conservation and ecologically led river restoration. An unintended consequence of the broad acceptance of CEMs as conceptual models for alluvial stream behaviour has been to help perpetuate the assumption that a single-thread, meandering channel represents the natural configuration of a dynamically stable alluvial stream and that this, consequently, represents a universally appropriate target morphology for restoration (see Kondolf (2009) for extended discussion of this point).

Reflecting on the history of human land use suggests that we should not be surprised that single-thread channels predominate in more economically developed countries since the late 19th and early 20th centuries. By then, anthropogenic disturbance of many multi-channel systems had already triggered widespread channel metamorphosis into single-thread configurations (Marston *et al*., 1995; Surian and Rinaldi, 2003). Actually, channel transformations to simpler confined forms were the specific intentions of many early settlement river management measures. Manipulating a multi-channel reach into a single-threaded channel not only improved waterway commerce but also enhanced drainage, opened bottom land for agriculture, facilitated construction of small dams for water abstraction or hydropower and allowed building of fewer, shorter bridges.

In the USA, beginning two centuries ago, floodplain wetland complexes were systematically drained and developed, the transformative engineering supported by public programmes (e.g. the Swamp Land Act of 1850) as a means of ceding 'waste' lands to the States. Two hundred thousand miles of streams were systematically channelized or embanked into single-thread configurations that were deeper, simpler and narrower (Schoof, 1980). These approaches to wetland, floodplain and stream management prevailed in the USA until the late 20th century (Dahl and Allord, 1996), when wetland restoration began (Lewis, 2001). Centuries earlier, similar wetland and river management had begun in Europe (Brookes, 1988). The outcome is that most streams in the global North currently have channel forms and relations to their floodplains that are the legacy of a century or more of systematic manipulation and inadvertent impacts on channel processes and fresh water ecology (Brown and Sear, 2008).

Recognizing that the single-thread channel is perhaps not necessarily the 'natural channel' that restoration would seek to emulate, Montgomery (2008, p.292) stated that '[T]he first step in a river-restoration program should instead be to develop a solid understanding of what the targeted rivers were actually like before the changes that restorationists seek to undo or mitigate'. Indeed, fluvial geomorphologists have for some time questioned the notion that stable, equilibrium channel forms exist at all (Phillips, 1992; 1999; 2009). Similarly, recognition of the ecological benefits of frequent and prolonged floodplain inundation, driven by flooding several times a year, has initiated the discouraging of 2-year (bankfull) flow event as the prime design discharge for stream restoration in Europe (Habersack and Piégay, 2008) and the USA (Doyle *et al*., 2007).

Accepting that a multi-channel configuration and increased floodplain inundation better represent the pre-disturbance condition of many alluvial streams, it may be argued that the CEMs could be extended by including a precursor stage. Recognition that multi-threaded channels and floodplains inundated several times per year may provide a great range of more valuable habitats, and so represent a valid design template for restoration, suggests that links between evolutionary stage and habitat attributes could be explored. Also, the ecological values provided by streams during different evolutionary stages need to be properly evaluated to facilitate river management and restoration decision making that is led ecologically, rather than morphologically.

FRAMEWORKS FOR UNDERSTANDING STREAM EVOLUTION

Review of existing channel evolution models

Morphological response to disturbance that involves channel incision may be considered in two dimensions: vertical adjustment involving degradation and aggradation of the bed and lateral adjustment involving retreat and advance of the banks (Little *et al*., 1981; Thorne *et al*., 1981). Vertical adjustments dominate initial responses driven by erosion and lowering of the bed until the banks become unstable, whereas lateral adjustment dominates as geotechnical bank failures and toe scour result in widening. Eventually, the width of the unstable channel becomes sufficiently large that near-bank flows lose their competence to entrain and remove failed bank material, so that channel width first stabilizes and then decreases as slumped bank material builds bank toe benches and berms at one or both margins. Provided

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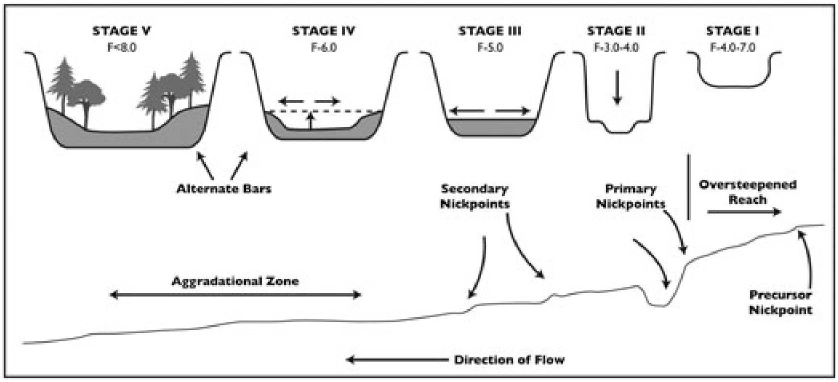

Figure 1. Schumm *et al*. (1984) Channel Evolution Model with typical width–depth ratios (F). The size of each arrow indicates the relative importance and direction of the dominant processes of degradation, aggradation and lateral bank erosion. (Redrawn with permission from Water Resources Publications)

that no further disturbance occurs, the channel recovers a dynamically meta-stable form when its banks and berms stabilize and the energy slope adjusts to match local sediment transport capacity to the supply of sediment from upstream (Simon and Thorne, 1996).

During the 1980s, identification that morphological response is usually characterized by bed degradation followed by bank collapse, widening and eventual stabilization led to the formulation of a generalized CEM by Schumm *et al*. (1984). The five-stage model of Schumm *et al*. is based on field monitoring of unstable streams in North Mississippi, and a space-for-time substitution that uses observations made simultaneously along the stream to indicate how channel changes at a given cross-section would occur through time if the reach were considered systematically (Figure 1). Simon and Hupp's (1986) six-stage model adaptation (Figure 2) was based on post-disturbance evolution of channelized streams in West Tennessee, although it has subsequently been shown also to apply in a wide variety of physiographic settings (Simon and Thorne, 1996).

The most obvious difference between the five-stage and six-stage CEMs is that Simon and Hupp include a

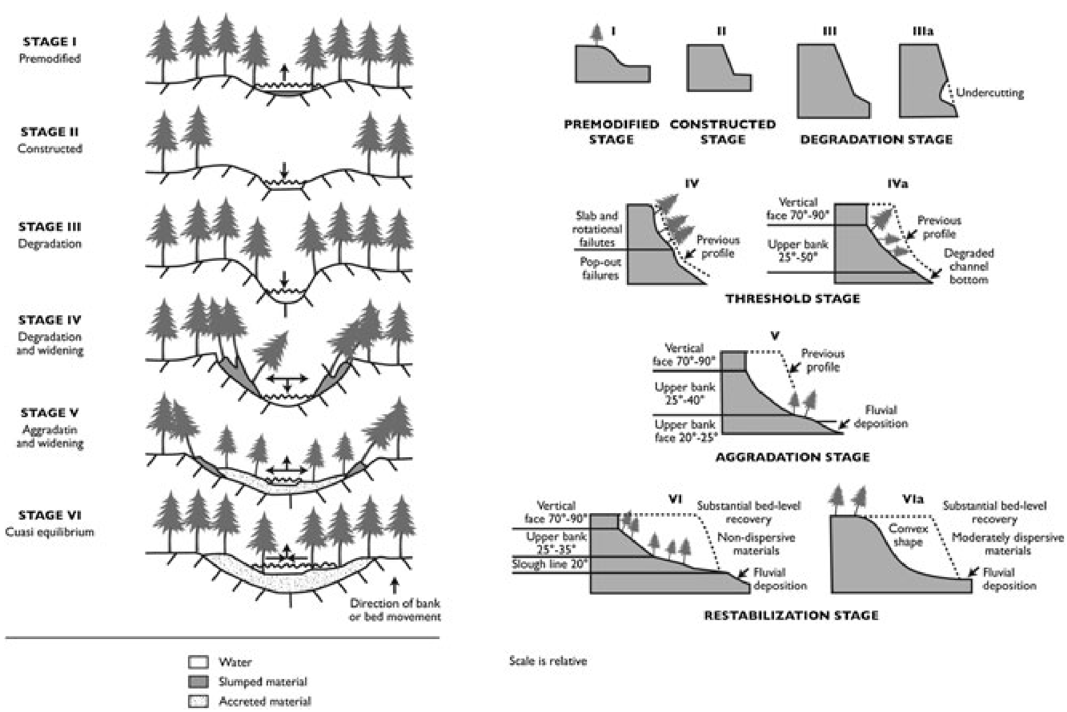

Figure 2. Simon and Hupp's (1986) Channel Evolution Model. [Adapted from Simon and Hupp (1986).]

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'constructed' stage between the 'pre-modified' and 'degradation' stages of Schumm *et al*. This stems from the common channelization, straightening and re-sectioning of streams in their study area. Hence, Stage III in Simon and Hupp's model corresponds to Stage II in the model of Schumm *et al*. in representing a condition where the channel is degrading, but bed lowering has not yet increased bank height sufficiently to trigger instability (Little *et al*., 1981; Thorne *et al*., 1981). A second difference is that bed scour continues in Stage IV of Simon and Hupp's model even though the banks are retreating because of geotechnical failure, simultaneously producing channel degradation and widening. This contrasts with the equivalent Stage III in the model of Schumm *et al*., which indicates that the bed elevation starts to aggrade once widening commences. The third difference between the CEMs is the greater emphasis placed on the influence of bank and riparian vegetation processes in Simon and Hupp's model; an emphasis subsequently validated by field research that established the effectiveness of vegetation as a 'riparian engineer' (Gurnell and Petts, 2006).

In the years following formulation of these CEMs, many of the incised channels from which the models were derived tended to stabilize as a result of natural recovery, assisted in many places by engineering stabilization (Simon and Darby, 2002). Despite this, evidence from long-term monitoring of late-stage evolution in these streams has revealed that significant changes to channel morphology continue beyond the end-stages in the original CEMs, through increases in sinuosity and roughness coupled with reductions in sediment load and mobility. Thorne (1999) reported late-stage morphological evolution featuring closing of back channels, invasion of sloughs and bar tops by vegetation, adoption of a sinuous path by the regime channel established during Stages V/VI and renewed bank retreat along the outer margins of developing meander bends in the evolving channel planform (Figure 3). This may partly explain why sediment concentrations have remained stubbornly high in many streams deemed, according to the established CEMs, to have recovered from incision (Shields, 2009). These late-stage evolutionary changes are widely observed, and Thorne (1999, page 118) proposed that 'an additional stage (Stage VI/VII) be added to existing CEMs to account for late-stage incised channel evolution from straight or braided to meandering'.

It is timely to further revise CEMs in two important respects. The first stems from consideration of extended histories of channel adjustment unavailable in the 1980s, which indicate that late-stage evolution may involve adjustments to channel planform not included in the existing models. The second arises because recent reconstruction of past fluvial environments based on the age and stratigraphy of valley-fill deposits in Europe and the Eastern USA challenges the general assumption that alluvial streams were predominately single threaded in their 'natural', pre-disturbance condition.

Physical evidence for precursor and successor stages

Walter and Merrits (2008) and Merritts *et al*. (2011) established that from the late 17th to early 20th centuries, settlement by Europeans altered streams throughout the Eastern USA through forest clearance (that increased flow and sediment yields) and the widespread construction of low (3–5 m high) but valley-wide mill dams, each of which created shallow reservoirs that inundated wetlands and deposited sediment, obscuring the pre-existing anastomosed channel networks. Once timber resources were depleted, agriculture dominated and other power sources had been developed, these mill dams were abandoned. They subsequently failed, and channel incision into the post-settlement, valley-fill deposits created single-threaded channels.

Walter and Merrits (2008) concluded that 'The current condition of single gravel-bedded channels with high, fine-grained banks and relatively dry valley-flat surfaces disconnected from groundwater is in stark contrast to the pre-settlement condition of swampy meadows (shrub-scrub) and shallow anabranching streams' (p.303), leading them to propose that seminal geomorphic studies including those performed by Leopold and Maddock (1953), Wolman

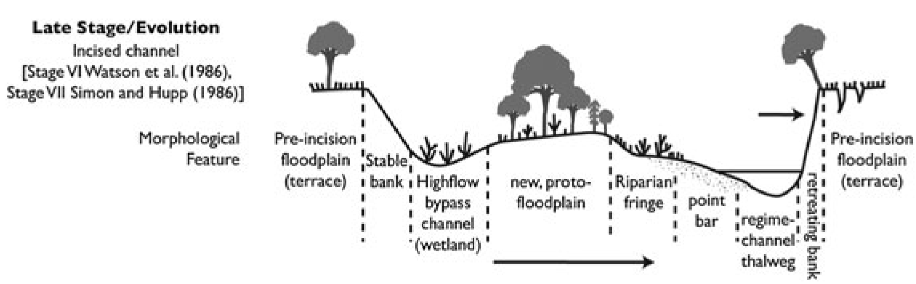

Figure 3. Late-stage morphological evolution involving development of cross-sectional asymmetry and planform sinuosity through closing of back channels, invasion of sloughs and bar tops by vegetation, adoption of a sinuous path by the regime channel established in Stages V/VI and renewed bank retreat along the outer margins of developing bends in the channel planform (modified from Thorne, 1999)

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(1955) and Wolman and Leopold (1957), which established relationships between the dominant discharge, channel form and floodplain building processes, were in fact based on channel and floodplain morphologies that were the products of prior anthropogenic disturbance.

Although controversial (e.g. Hupp *et al*., 2013), these findings are neither particularly new nor unique to the Eastern USA. Paleohydrological studies in Europe have established that channel–floodplain associations once thought to be ‘natural’ actually represent the outcomes of accelerated sediment production and deposition that buried multi-threaded woodland stream systems (Harwood and Brown, 1993; Sear and Arnell, 2006; Brown and Sear, 2008). In the Pacific Northwest (Collins *et al*., 2003; Pollock *et al*., 2003; Montgomery, 2004) and Intermountain (Woelfle-Erskine *et al*., 2012) regions of the Western USA, several authors demonstrate that multi-threaded networks of branching streams and connected wetlands were common prior to European settlement, where single-thread channels and relatively dry floodplains currently occupy ‘intact’ alluvial valleys.

Similarly, historical reconstructions of valley sediments throughout the California Coastal Range show that branching stream channels (Tompkins, 2006) and wetlands (Grossinger *et al*., 2007) were commonplace in basins prior to European settlement and land management for drainage and flood control. It is important to note that the Mediterranean climate of this region resulted in seasonal drying of some pre-disturbance branching channel systems, but Kondolf and Tompkins (2008) ascertained that these still provided richer aquatic habitat than the post-disturbance regulated and contracted perennial single-thread channels that replaced them.

The remaining global extent of network channels is concentrated in less developed countries and to stream systems where the scale is too large (e.g. Okavango Delta, Sudd Swamp in the Nile basin and Florida Everglades) or the location too remote (e.g. glacial outwash plains and mountain meadows) for river and floodplain management to be effective in eliminating them. Recent field research in light of conceptual CEMs prompts the consideration that the single-thread configuration taken to represent the initial, undisturbed morphology of an alluvial stream may have actually evolved from earlier, truly pre-disturbance, multi-channel morphologies that were not only more extensive and complex but also provided greater diversity and richer habitats and ecosystem functions. There is, thus, a case for adding a precursor branching stage to the existing CEMs and for integrating habitat and ecosystem benefits into the model framework.

The stream evolution model

In light of the issues and arguments set out above, we developed a SEM by combining the stages featured in the original CEM models (Schumm *et al*. (1984); Simon and Hupp (1986)), inserting a precursor stage to better represent pre-disturbance conditions and adding two successor stages to cover late-stage evolutionary changes missing from the original models (Table I). We also represent channel evolution in the SEM as a cyclical rather than a linear sequence. This modification stems from the fact that early models represent channel response as progressing linearly through a sequence of stages (see Figures 1 and 2) whereas evidence from the stratigraphy of Holocene valley-fill deposits and field monitoring of changes in contemporary, incised channels indicates that evolution in disturbed fluvial systems is *cyclical* (e.g. Hawley *et al*., 2011). A common criticism of the original CEMs is that it is rare for a stream to exhibit all of the stages in the model and even rarer for them to occur in the indicated sequence. For example, a reach may experience repeated episodes of incision and rapid widening (Stages II and III of Schumm *et al*. or Simon and Hupp’s Stages III and IV) without recovering any of the lost bed elevation through intervening episodes of aggradation (Bledsoe *et al*., 2007). We suggest that these and other behaviours could be better represented as non-linear responses and ‘short-circuits’ in a cyclical SEM, as illustrated in Figure 4.

STREAM EVOLUTION MODEL STAGE LINKED TO HABITAT AND ECOSYSTEM BENEFITS

Background and approach

Stream morphology interacts with the flow and sediment regimes (discharge, seasonality and variability), channel boundary characteristics (bed sediments, bank materials and vegetation) and water quality (temperature, turbidity, nutrients and pollutants) to produce, maintain and renew habitat at a range of spatial and temporal scales. The potential for a stream to support resilient and diverse ecosystems generally increases with its morphological diversity, although restoration of lost diversity does not guarantee recovery of any particular target or iconic species, which may be limited by factors unrelated to stream morphology (Palmer *et al*., 2005).

It follows that the morphological adjustments experienced by unstable, incising streams have serious implications for the diversity and richness of habitat and ecosystem services it can provide. Despite this, no attempt has been made, to date, to identify and evaluate the habitat and ecosystem benefits associated with evolutionary stage. To address this gap in knowledge, we performed a systematic exploration of links between the physical and vegetative attributes of the stream and the habitat and ecosystem benefits it provides for the eight stages in the SEM. Streams were assessed per stage on the basis of the authors’ interpretations of processes and physical attributes coupled with assessment of information compiled from published relationships between

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Table I. Previous Channel Evolution Models and the proposed Stream Evolution Model with description of reach-average characteristics, or stages

Schumm *et al*., 1984	Simon and Hupp, 1986	SEM		Description
		0. Anastomosing		Pre-disturbance, dynamically meta-stable network of anabranching channels and floodplain with vegetated islands supporting wet woodland or grassland. $Qs_{in} \geq Qs_{out}$, $h \ll h_c$
I. Undisturbed	I. Pre-modified	- Single Thread Channels -	1.Sinuous	Dynamically stable and laterally active channel within a floodplain complex. Flood return period 1-5 yr range. $Qs_{in} \geq Qs_{out}$, $h \ll h_c$
	II. Constructed		2. Channelized	Re-sectioned land drainage, flood control, or navigation channels. $Qs_{in} \leq Qs_{out}$, $h > h_c$
II. Degradation	III. Degradation		3. Degrading	Incising and abandoning its floodplain. Featuring head cuts, knick points or knick zones that incise into the bed, scours away bars and riffles and removes sediments stored at bank toes. Banks stable geotechnically. $Qs_{in} < Qs_{out}$, $h > h_c$
			3s. Arrested degradation	Stabilized, confined or canyon-type channels. Incised channel in which bed lowering and channel evolution have been halted because non-erodible materials (bed rock, tight clays) have been encountered. $Qs_{in} \sim Qs_{out}$, $h > h_c$
III. Rapid Widening	IV. Degradation and widening		4. Degradation and widening	Incising with unstable, retreating banks that collapse by slumping and/or rotational slips. Failed material is scoured away and the enlarged channel becomes disconnected from its former floodplain, which becomes a terrace. $Qs_{in} < Qs_{out}$, $h > h_c$
			4-3. Renewed incision	Further head cutting within Stage 4 channel. $Qs_{in} < Qs_{out}$, $h \gg h_c$
IV. Aggradation	V. Aggradation and widening		5. Aggrading and widening	Bed rising, aggrading, widening channel with unstable banks in which excess load from upstream together with slumped bank material build berms and silts bed. banks stablizing & berming. $Qs_{in} > Qs_{out}$, $h \sim h_c$
V. Stabilization	VI. Quasi-equilibrium		6. Quasi-equilibrium	Inset floodplain re-established. quasi-equilibrium channel with two-stage cross-section featuring regime channel inset within larger, degraded channel. Berms stabilize as pioneer vegetation traps fine sediment, seeds and plant propagules. $Qs_{in} \sim Qs_{out}$, $h < h_c$
	VII. [1]Late-stage evolution		7. Laterally active	Channel with frequent floodplain connection develops sinuous course, is laterally active and has asymmetrical cross-section promoting bar accretion at inner margins and toe scour and renewed bank retreat along outer margins of expanding/migrating bends. $Qs_{in} \geq Qs_{out}$, $h \ll h_c$
		8. Anastomosing		Meta-stable channel network. Post-disturbance channel featuring anastomosed planform connected to a frequently inundated floodplain that supports wet woodland or grassland that is bounded by set-back terraces on one or both margins. $Qs_{in} \geq Qs_{out}$, $h \ll h_c$

[1] Suggested by Thorne (1999)

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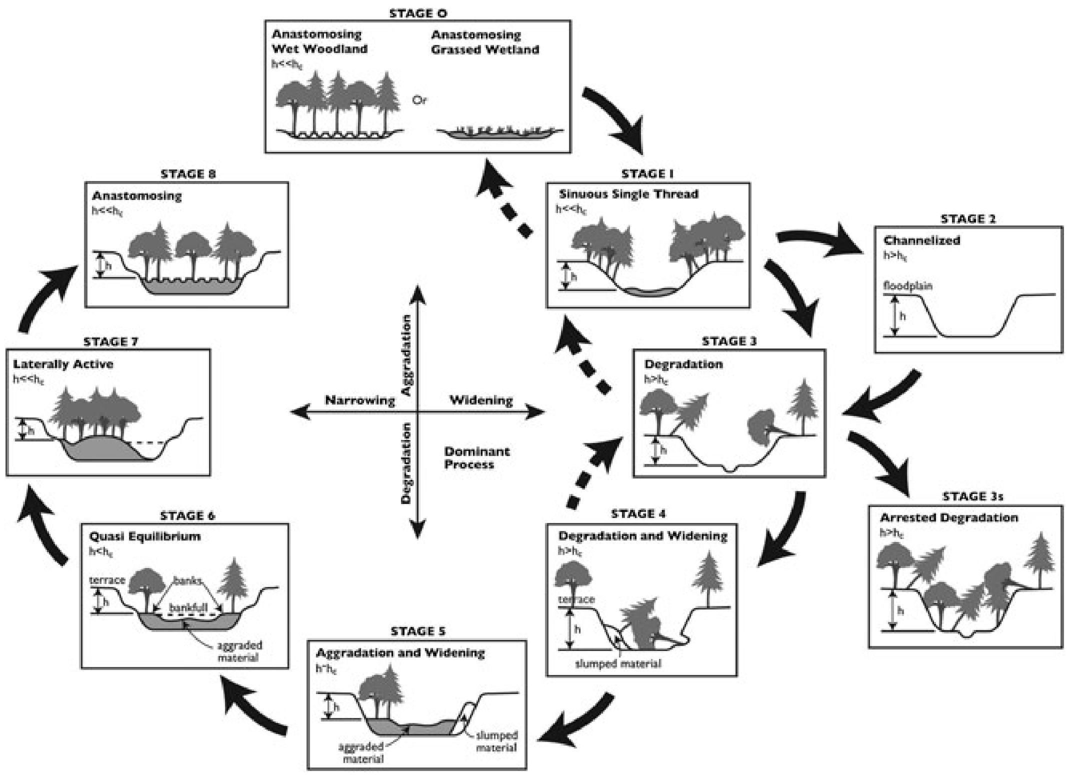

Figure 4. Stream Evolution Model based on combining the Channel Evolution Models in Figures 1–3, inserting a precursor stage to better represent pre-disturbance conditions, adding two successor stages to cover late-stage evolution and representing incised channel evolution as a cyclical rather than a linear phenomenon. Dashed arrows indicate 'short-circuits' in the normal progression, indicating for example that a Stage 0 stream can evolve to Stage 1 and recover to Stage 0, a Stage 4-3-4 short-circuit, which occurs when multiple head cuts migrate through a reach and which may be particularly destructive. Arrows outside the circle represent 'dead end' stages, constructed and maintained (2) and arrested (3s) where an erosion-resistant layer in the local lithology stabilizes incised channel banks

stream attributes, functional habitats and freshwater ecology (e.g. Harper *et al*., 1995; Padmore, 1997; Newson and Newson, 2000), and synthesis of newly available knowledge gained from recent publications that have established linkages between ecosystem functions and common stream types (e.g. Thorp *et al*., 2010).

In this evaluation, the physical attributes considered for the stream were hydrologic, hydraulic and geomorphic. Such is the importance and influence of vegetation that it was dealt with as a separate attribute of the stream environment. On the basis of the physical and vegetative attributes of the stream, habitat and ecosystem benefits were evaluated in terms of habitat, biota, resilience and persistence, and water quality. The bases on which the evaluations were performed are described in the following sections, with details of each stage's unique attributes listed in Tables II and III.

Hydrologic regime

The hydrological regime is crucial to creating and maintaining morphological diversity and supporting ecological integrity, underscoring its significance to channel change. All elements of the regime are important, ranging from base flows (and periods of zero discharge in ephemeral streams) to flood events that provide the 'flood pulse advantage' (Junk *et al*., 1989; Poff *et al*., 1997). Timing and seasonality are also significant with, for example, secondary production and selection for flood-linked life history characteristics depending on the flood pulse occurring during late spring or summer (Thorpe *et al*., 2006).

From the perspective of the SEM, stages involving channelization, dredging or incision that concentrate flows within the channel to accentuate flood peaks may damage or wash out physical and habitat features and diminish floodplain interactions. Conversely, the attenuating effects of floodplain and multi-channel morphologies and enhanced capacity to store sediment associated with other SEM stages tend to enhance flood-related morphological features and ecological benefits.

Floodplain connectivity also influences the types, quantities and qualities of hydrological benefits provided by floods: benefits that are central to the productivity of aquatic, riparian and floodplain ecosystems. Floodplains absorb, retain and then release floodwater, increasing the

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Table II. Physical and vegetative attributes for each stage in the Stream Evolution Model

SEM Stage		Physical Attributes			Vegetation Attributes
		Hydrologic Regime	Hydraulics and Substrate	Dimensions and Morphology	
0. Anastomosing. Dynamically meta-stable network of anabranching channels with vegetated islands.		Floods diffused over the full width of the floodplain so flood peaks are maximally attenuated. Flood pulses diffused and subdued. High water table and close connection between stream flow and ground water ensures reliable base flows and continuous hyporhesis, though flow in smaller anabranches may be ephemeral.	Multiple channels provide maximum in-channel hydraulic diversity through partition of discharge between branches that widens range of in-channel depth/velocity combinations. Anabranches create multiple, marginal deadwaters. Wide range of substrate grain sizes arranged into numerous, well-sorted bed patches.	Multiple anabranches, islands and side channels maximize. Morphological features abound in-channel and on the extensive and fully connected floodplain, providing a high capacity to store sediment and wood and supporting diverse wetlands. Bank heights are low with stability enhanced by riparian margins, but some river cliffs are generated by localised erosion. Network and floodplain are highly resilient to disturbance, buffering the system.	Frequent, small channel adjustments and high, reliable water table create ubiquitous settings for proliferation and succession of aquatic, emergent, riparian and floodplain plants. Wet woodlands on islands and floodplain supply and retain wood, and widespread vegetation proximal to channels produces abundant leaf litter.
Single Thread Channels	**1.Sinuous, single-thread .** Stable and laterally active. Sediment sorting and transfer.	Floods up to bankfull discharge retained in-channel reducing attenuation. Larger floods still spill to floodplain, attenuating their peaks. Close connection between groundwater and stream flow ensures reliable base flows and good hyporhesis.	Range of in-channel depth/velocity combinations up to bankfull flow provides moderate hydraulic diversit and frequent deadwaters along remaining channel boundaries. Substrate sorting varies between thalweg and alternate or point bars, with different degrees of armoring. Variation in bed morphology continues to supports a high degree of substrate patchiness.	Wetted area relative to flow, shoreline length and complexity decrease due to switch to single channel. Though bedforms and bars remain widespread, frequency of islands, confluences and diffluences is greatly reduced, adversely affecting capacity to store sediment and wood. Higher banks are less stable with river cliffs found along outer margins of bends. Floodplain extent and connectivity undiminished, but number of side channels and functionality of connected wetlands reduced.	Decreases in hydraulic and morphological diversity trigger reductions in quantity and quality of aquatic, riparian and, especially, emergent plants. Floodplain communities remain diverse, but transition from wetland to more terrestrial assemblages. Reductions in extent of woodlands due to switch from multiple to a single channel decrease recruitment of wood and leaf litter.
	2. Channelized. Re-sectioned land drainage, flood control, or navigation channels.	Flood flows retained in-channel up to design discharge, enhancing flood pulses. Flood attenuation reduced. Efficient drainage speeds post-flood recession and lowers groundwater, so base flows and hyporhesis are impaired.	Artificially high in-channel discharge capacity coupled with uniformity of depth/velocity combinations reduces hydraulic diversity and compromises functionality of any marginal deadwaters. Bed substrate scoured, with sorting impacted and patchiness reduced through extreme armoring or paving.	channelization reduces wetted area, shoreline length and complexity relative to flow. Some bedforms and bars remain but islands, side channels, and confluences/diffluences are eradicated. Capacity to store sediment and wood reduced, or eliminated by channel maintenance. Banks stable or revetted, with river cliffs eliminated. Extent, connectivity and functionality of riparian zone, floodplain and wetlands all diminished.	Aquatic and emergent plants destroyed during construction with recovery limited to patches and narrow belts. Riparian plants only contribute wood and leaf litter if some of riparian corridor is left in place. Floodplain vegetation communities disconnected from channel may transition further to terrestrial assemblages.
	3. Degrading. Incising and abandoning its floodplain. Banks stable geotechnically.	Concentrates progressively greater flood peaks in-channel, further amplifying flood pulse Flood attenuation ineffective. Groundwater recharge is minimal, making base flow unreliable. Hyporheic zone damaged or destroyed by scour at bed and bank toes.	Bed lowering, removal of bars and riffles and scour a bank toes reduces hydraulic diversity means there are few, if any, marginal deadwaters. Bed substrate continues to be scoured, with sorting impacted and patchiness reduced through extreme armoring or paving.	Degradation reduces wetted area, shoreline length and complexity relative to flow compared to Stage 1. Bedforms, bars and islands scoured, confluences/diffluences eradicated and side channels, floodplain and wetlands abandoned. Capacity to store sediment and wood effectively lost. Banks mostly stable with local river cliffs. Functionality of the riparian zone is diminished due to reduced connectivity with channel.	Aquatic and most emergent plants destroyed by incision; only seasonal and annual species remain. Riparian vegetation undercut and increasingly unstable leading to artificially elevated inputs of wood. Input of leaf litter, seeds and propagules continues, but retention reduced. Floodplain vegetation stressed due to lower water table.
	3s. Arrested degradation. Confined or canyon-type channels.	Concentrates a wide range of flood peaks, providing no effective flood attenuation and maximal flood pulse effects. Groundwater recharge is minimal, base flow unreliable and hyporheic zone remains damaged or destroyed.	Similar to Stage 3, though there may be some limited recovery of hydraulic diversity due to presence of invasive or remnant riparian plants and accumulation of log jams formed by tress that have fallen into the degraded channel. Limited sediment retention, sorting and patch development.	Natural or artificial stabilization locks in dimensions and morphology developed in Stage 3. Limited capacity to store sediment and wood once degradation ceases. Banks mostly stable but extent of river cliffs may increase. Functionality of the riparian zone remains diminished and channel is permanently disconnected from its floodplain and wetlands.	Relative stability allows for early succession in emergent and riparian plant communities, improving supply of leaf litter. Wood recruitment continues, limited by the proximity, width and contiguity of woodlands on surrounding floodplain and terrace surfaces.
	4. Degradation and widening. Incising with unstable, retreating banks.	Concentrates an extreme range of flood peaks, negating flood attenuation and furthe amplifying flood pulse effects. Groundwate recharge, base flow generation and hyporheic connectivity are all dysfunctional	Hydraulic diversity remains low due to channel scour and efficient downstream transport of woody debris. Deadwaters continue to be absent or dysfunctional. Bed scour continues to adversely impact substrate sorting and patchiness.	Sediment inputs from bank retreat initiates limited bedform and ba development, but mass failures eliminate stable banks and increase the extent of river cliffs that destroy riparian margins. Wetted area, shoreline length and complexity relative to flow all remain low. No recovery of capacity to store sediment and wood, and floodplai still disconnected.	Aquatic plant community remains dysfunctional due to on-going bed degradation and riparian plants are destroyed by rapid widening. Wood recruitment may increase if banks are forested, though retention depends on trees being large relative to increasing channel width.
	4-3. Renewed incision. Further head cutting within Stage 4 channel.	Increased range of floods retained in-bank continues to amplify flood pulse effects. Flood attenuation, groundwater recharge, base flow generation and hyporheic connectivity all remain dysfunctional.	Renewed incision maintains limited range of depth/velocity, combinations and so hydraulic diversity remains low. No new marginal deadwaters are created. Channel scour effectively eliminates functionality of substrate sorting and patchiness in providing habitat and ecosystem benefits.	Renewed scour removes embryonic bedforms and bars formed in Stage 4. Degree of disconnection of side channels, floodplain and wetlands due to channel incision increases. Any stored sediment o wood is flushed downstream. Continued bank retreat forms river cliffs that erode any remaining riparian fringe.	Aquatic, emergent, riparian and floodplain plant communities all depleted and dysfunctional. Low supply of leaf litter but wood recruitment maintained until proximal supply is exhausted. Retention depends on trees being large relative to increasing channel width.
	5. Aggrading and widening. Bed rising, banks stablising & berming.	No significant improvement in flood attenuation but flood pulse effects not quite as marked. Groundwater recharge remains dysfunctional, and base flows are still unreliable, but some hyporheic connectivity is recovered.	Aggradation renews depth/velocity variability that to improve hydraulic diversity. Small marginal deadwaters may develop, but these are not yet functional in providing habitat and ecosystem benefits. Bars and log jams begin to improve sediment sorting and patchiness.	Wetted area, shoreline length and complexity relative to flow all remain low. Aggradation generates some bedforms and bars but channel remains dysfunctional with regard to effective storage of sediment and wood. Bank stability improves marginally compared to Stage 4 allowing some recovery in riparian fringe. Floodplain connectivity begins to recover due to aggradation at bed and berm formation at banks.	Some return of aquatic plants. Bars and berms provide opportunities for emergent and riparian plants. Floodplain plant community remains isolated from channel physically and hydrologically. Widening may continue to recruit wood if there are proximal trees and supply of leaf litter may be renewed as well.
	6. Quasi-equilibrium. Regime channel and proto-floodplain re-established.	Remains disconnected from former floodplain, but increased boundary roughness and emergent riparian stands damp flood pulse effects and reintroduce some flood attenuation. Groundwater recharge and base flow functions begin to recover and hyporhesis continues to improve.	Developing regime channel interacts with proto-floodplain surfaces to dissipate energy and increase hydraulic diversity. Accumulation of sediment and colonization of bars and berms by emergent and riparian vegetation increases number and functionality of marginal deadwaters. Patches of contrasting substrate size and sorting develop accordingly.	Wetted area, shoreline length and complexity relative to flow all remain low. Bedforms and bars recover to pre-disturbance levels restoring some capacity to storage of sediment and wood. Bank stability continues to improve at expense of river cliffs, allowing further recovery in riparian fringe. Floodplain connectivity continues to recover and new side channels may be created, thoug wetlands remain disconnected.	Relatively stable channel margins and inset features provide sites for development of aquatic, emergent and riparian plant communities. Aggradation improves connectivity with and functionality of floodplain plants, maintaining wood recruitment and enhancing supply of leaf litter.
	7. Laterally active. Regime channel develops sinuous course.	Increases in flow resistance due to development of channel and inset floodplair roughness further damp flood pulse effects while returning groundwater recharge, base flow and hyporheic functionality back close to Stage 1 level.	Development of planform sinuosity and interaction with maturing floodplain enhance hydraulic diversity and make marginal deadwaters fully functional. Substrate sorting enhanced and patchiness becomes fully functional. Hydraulic and substrate attributes recover to Stage 1 levels.	Growth of sinuous channel increases wetted area, shoreline length and complexity. Bedforms and bars persist and new islands, confluences and diffluences develop, increasing capacity to storag of sediment and wood. Renewed bank erosion at bends broadens range of bank morphologies. Extent of new side channels increase with some wetlands created.	Extent of riparian and floodplain plant communities increases at expense of opportunities for emergent plants. Stabilisation of banks reduces wood recruitment but extension and maturing of riparian and floodplain communities maintain supply of leaf litter.
8. Anastomosing. Meta-stable anabranching network.		Hydrologic attributes and functions similar to Stage 0 but network inset within the channel created in Stage 4 as modified in Stage 7.	Hydraulic and substrate attributes and functions similar to Stage 0, but network inset within the channel created in Stage 4 as modified in Stage 7.	Morphological attributes and functions similar to Stage 0, but wetted area, shoreline length, and extent of floodplain and its features diminished because network is inset within the valley created in Stage 4.	Hydrological, hydraulic and morphological attributes and functions similar to those of Stage 0 allow vegetation attributes to recover to pre-disturbance levels.

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Table III. Habitat and ecosystem benefits for each stage in the Stream Evolution Model

SEM		Habitat and Ecosystem Benefits			
		Habitat	Biota (see Thorpe et al., 2010)	Resilience and Persistence	Water Quality
0. Anastomosing. Dynamically meta-stable network of anabranching channels with vegetated islands.		Multiple channels, islands and broad floodplain provide access to rich palette of diverse habitats in close proximity and refugia across a wide range of flood events. High water table, deep pools and continuous hyporhesis provide drought refugia in the multiple channels. Channel margins evolve semi-continuously to expose tree roots.	Multiple, complex, dynamic channels that are connected to an extensive floodplain and which interact with groundwater and hyporhesis support large numbers of different species. This provides for the highest possible biodiversity (species richness an trophic diversity), proportion of native species, and 1st and 2nd order productivity.	Physical and vegetative attributes and functions stemming from their complexity, connectivity and diversity act to attenuate floods and sediment pulses, making habitat and biota persistent and highly resistant to natural and anthropogenic disturbances including flood, drought, and wild fire.	High capacity of multi-channel network to store sediment and cycle nutrients and other suspended solids produces exceptional water clarity. Dense, diverse proximal vegetation provides abundant shade which, together with efficient hyporhesis, is highly effective in ameliorating temperatures.
- Single Thread Channels -	**1.Sinuous, single-thread.** Stable and laterally active. Sediment sorting and transfer.	Palette of habitats somewhat reduced and range of flood refugia decreased though still high. Continued hyporhesis coupled with deeper scour pools in the single-thread channel provide excellent drought refugia. Reduction in length of shoreline decreases extent of exposed roots.	Single-thread channel connected to its floodplain. Channel still provides a good range of valuable habitat primarily at its margins, though reductions in morphological complexity and bankline length impac biodiversity and mean that biodiversity and productivity are moderate rather than high.	Sinuous channel form and close connectivity with floodplain, groundwater and hyporheic zones maintains high resilience to disturbance. Flood and drought resilience slightly reduced compared to that provided by the multi-channel system in Stage 0 due to some loss of effectiveness in attenuating floods.	Sediment storage and nutrient cycling capabilities slightly reduced but clarity still good in single channel/floodplain configuration. Temperature amelioration maintained due to effective shade and hyporhesis in channel/floodplain system.
	2. Channelized. Re-sectioned land drainage, flood control, or navigation channels.	Construction of trapezoidal cross-section, imposition of uniform morphology and isolation from floodplain destroys most habitat and disables functionality with respect to provision of flood and drought refugia. Exposed tree roots are removed during construction.	Disturbance due to channelization is too rapid to allow many species (especially native species adapte to pre-disturbance conditions) time to adapt. As a result species richness and trophic diversity collapse, while 1st and 2nd order productivity declines markedly.	Simple geometry of constructed channel likely to change through aggradation, degradation or lateral migration unless bed level is fixed by structures and banks are revetted. Habitat and ecosystem benefits are vulnerable to disturbance and have negligible resilience to floods and droughts.	Wide range of flows concentrated into simplified channel without floodplain connection results in low water clarity and limited nutrient cycling. Poor temperature amelioration due to lack of riparian shading and ineffective hyporheic exchange.
	3. Degrading. Incising and abandoning its floodplain. Banks stable geotechnically.	Degradation destroys benthos, removes features that provide in-channel habitat and isolates channel from floodplain habitat. Channel scour and disconnection from floodplain mean that flood and drought refugia are destroyed or dis-functional. Tree roots exposed by bank scour.	Disturbance due to degradation is severe although some species have adapted to cope with this fluvial phenomenon, which occurs naturally as being generated anthropogenically. Species richness and trophic density still decrease with adverse impacts on 1st and 2nd order productivity.	Degradation makes remaining habitat and ecosystem benefits highly sensitive to disturbance in response to alterations to the flow and sediment regimes associated with, for example, climate or land-use changes. Resilience to flood and drought is negligibl	Functions responsible for water clarity and nutrient cycling further weakened due to bed scour, vegetatio destruction loss and reduced groundwater interaction. Effective temperature amelioration impaired by lack of shade and poor hyporheic exchange.
	3s. Arrested degradation. Confined or canyon-type channels.	Loss of habitat and/or disabling of functions incurred in Stage 3 are perpetuated in the confined, incised channel that results from arrested development when a degrading channel encounters highly erosion-resistant materials.	Suitably adapted species will colonise the confined, incised channel provided it remains stable, increasing 1st and 2nd order productivity. Species richness, trophic density and proportion of native species will, however, remain low.	Erosion-resistant bed and bank materials stabilize the boundaries of a confined, incised channel this marginally reduces habitat and ecosystem sensitivity to disturbance and provides limited flood and drough resilience.	Functions responsible for water clarity and nutrient cycling remain ineffective. Temperature amelioration may recover if stable banks support riparian vegetation sufficiently tall to provide effective shade.
	4. Degradation and widening. Incising with unstable, retreating banks.	Continued degradation further damages benthos, bedform and bar features, preventing recover of in-channel habitats and increasing isolation from the floodplain. Bank instability destroys riparian habitat but does expose some tree roots.	Continued disturbance due to bed degradation and rapid bank retreat that destroy habitat result in low levels of biodiversity, and 1st and 2nd order productivity being sustained in Stage 4. The proportion of native biota cannot recover.	Degradation and rapid bank retreat exposes remainin habitat and ecosystem benefits to disturbance and negates their flood and drought resilience.	Physical attributes responsible for providing water clarity and nutrient cycling remain dysfunctional. Bank instability and rapid widening removes riparian shade, negating capability for temperature amelioration.
	4-3. Renewed incision. Further head cutting within Stage 4 channel.	Continued bed scour and bank retreat mean that no recovery in the range, proximity or connectivity of habitat is possible, though further enlargement of channel may improve its functionality in providing refugia during floods.	Cycles of incision and rapid bank retreat prevent recovery of habitat, perpetuating low levels of biodiversity, and leading to collapse of 1st and 2nd order productivity The proportion of native biota remains low.	Renewed incision and bank instability maintains the heightened sensitivity of residual habitat and ecosystem benefits to disturbance and prevents any recovery of flood and drought resilience.	Renewed incision, bank instability and widening reduce remaining capacity of the physical and vegetative attributes of the channel to provide habitat and ecosystem benefits with respect to water quality.
	5. Aggrading and widening. Bed rising, banks stablising & berming.	Channel remains impoverished with respect to provision of rich and diverse habitat dysfunctional with respect to drought refuge. Creation of bedforms and bars at the aggrading bed may provide limited refuge during floods.	Reinstatement of some benthic sediments and in-channel features is reflected in some recovery in 1st and 2nd order productivity. However, at this stage biodiversity and the proportion of native biota have yet to respond.	Return of benthic sediments and in-channel features allow channel to absorb at least small disturbances without destroying habitat. Enlarged channel dimensions and conveyance tend to increase resilienc to floods though not droughts.	Re-creation of bedforms, bars and berms together with return of aquatic, emergent and riparian vegetation re-activate sediment storage and nutrient cycling functions, though water clarity and capacity for temperature amelioration remain limited.
	6. Quasi-equilibrium. Regime channel and proto floodplain re-established.	Some improvement in palette of accessible habitat, matched by provision of limited flood refuge and exposed roots from recovery of some in-channel features and vegetation. Reconnection of channel to groundwater and hyporheic zones result in some drought refugia.	Quasi-equilibrium, coupled with recovery of floodplain and hyporheic connectivity supports limited improvements in species richness and trophic diversity and allows some native biota to return. 1st and 2nd order productivity continues to increase as a result.	Quasi-equilibrium channel increasingly able to absorb moderate disturbances to flow and sediment regimes without loss of habitat and ecosystem benefits. In-channel features, vegetation, and floodplain connectivity and hyporhesis afford moderate flood and drought resilience.	Increases in the extent of the inset floodplain and riparian zones, vegetation re-growth and re-establishment of hyporheic connectivity provide moderate functionality for clarity and temperature amelioration, though nutrient cycling remains weak.
	7. Laterally active. Regime channel develops sinuous course.	Further improvement in range, quality and accessibility of habitat, coupled with improved functionality in terms of flood and drought refugia. Habitat benefits similar to Stage 1 channel, though habitat palette somewhat smaller.	The wider range of habitat in the increasingly diverse channel supports further improvement in biodiversity while native species colonise and use the sinuous channel and developing floodplain. Productivity remains moderate.	Disturbances to channel increasingly ameliorated by flow and sediment storage on developing floodplain, though sensitivity remains higher than in Stage 1 due to its smaller extent. Flood and drought resilience similarly limited.	Plant succession and maturing floodplain and riparian zones increase efficiency of nutrient cycling and provision of shade. Water clarity remains moderate but temperature amelioration further improved.
8. Anastomosing. Meta-stable anabranching network.		Multi-channel complexity produces further improvement in habitat palette. Longer banklines provide more extensive areas with exposed roots, but loss of deepest pools reduces performance of flood refugia during the most extreme events.	Renewed habitat diversity, richness and connectivity allow native biota to re-occupy the area, with levels of biodiversity and productivity recovering to pre-disturbance levels, albeit on the somewhat smaller palette provided in Stage 8.	Physical and vegetative attributes and functions of Stage 8 channel make habitat and biota persistent and highly resistant to natural and anthropogenic disturbances, though levels cannot match those of Stage 0 due to restricted size of inset floodplain.	Multi-channel network with connected floodplain, hyporheic exchange and mature plant communities supports excellent water clarity, temperature amelioration, and optimal nutrient cycling.

hydroperiod, slowing times to concentration, attenuating downstream flood peaks and recharging aquifers that keep floodplains moist and contribute to base flows. Base flow is an important hydrologic attribute because it governs habitability and biodiversity for aquatic species (Bêche *et al*., 2009).

Stream hydrology interacts with groundwater via the hyporheic zone (the part of the subsurface hydrological system beneath and adjacent to the channel that is closely coupled to the stream and with which water is exchanged freely) to increase the capability of the watercourse to support a diverse range of valuable habitats, especially during low flows (Boulton *et al*., 1998). The dimensions and contribution of the hyporheic zone may be large. For example, the hyporheic zone of the Flathead River, Montana extends laterally for 2 km and supplies more than half of the nutrients available to the aquatic ecosystem (Stanford and Ward, 1988). Connectivity between the stream and the

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hyporheic zone may be limited and even severed during some stages in the SEM by channelization, incision and/or the ingress of fines into coarse channel substrates.

Hydraulics

Research in the field of ecohydraulics has for several years focused on the influences of velocity and depth on channel habitats for fish and other aquatic species (Gordon *et al.*, 1992), whereas the importance of the stream providing a range of velocity–depth combinations to support a wide range of species through all their life stages has been demonstrated through numerous applications of models such as IFIM (Bovee *et al.*, 1998). Hydraulic diversity not only supports quality and variety in aquatic habitats but also interacts with bedforms and drives bed material and substrate sorting processes that contribute to diversity in benthic habitat.

Newson and Newson (2000) showed how the hydraulic characteristics of channels could be categorized using physical biotopes and functional habitats identified from the configuration of the water surface (Figure 5). The ecological benefits provided by the stream depend not only on the extent and variety of biotopes but also on their pattern, positioning and patchiness, as well as the extent to which hydraulic diversity is maintained across a range of discharges. For example, deep pools are vital in providing aquatic habitats linked to cool, hyporheic flows during hot, dry periods (Baxter and Hauer, 2000), whereas marginal deadwaters concentrate nutrients, provide rearing habitats during normal flows and act as refugia during floods (Lancaster and Hildrew, 1993; Schwartz and Herricks, 2005).

From the perspective of the SEM, the extent and persistence of key physical attributes such as hydraulic diversity and the existence of marginal deadwaters are likely to be evolutionary stage dependent.

Geomorphic attributes

Although debate continues between geomorphologists and ecologists regarding the relative contributions to habitat quality and diversity made by different channel forms and features (e.g. King and Tharme, 1993; Williams, 2010), it is generally agreed that supporting ecosystems with habitats that are rich and resilient, that range from micro-scale to meso-scale, to macro-scale, and that persist across a wide range of hydrologic conditions is vital. Consequently, significant geomorphic attributes include the dimensions, geometry, substrate characteristics and sediment features of the channel, as well as the equivalent attributes of those portions of the hydrologically and hydraulically connected floodplain.

Channel dimensions and geometry. Metrics selected to represent the physical size and channel shape are wetted area and the length and complexity of the shoreline. The utility of these attributes may be illustrated by considering that at all in-bank flow depths, a stream provides a larger wetted area and a longer, relatively more complex shoreline when it has a varied cross-section. It follows that for a given flow capacity, streams with multi-channel morphologies provide more shoal and edge habitat than equivalent streams with single-threaded channel configurations.

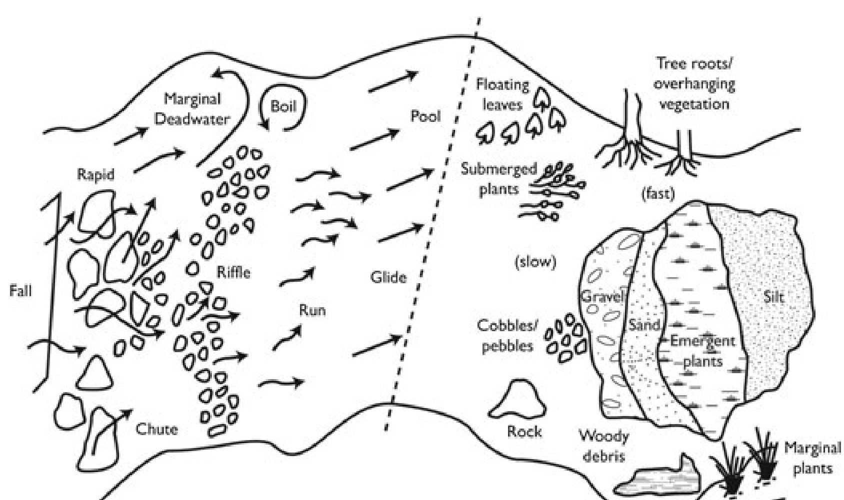

Figure 5. Physical biotopes and associated functional habitats suggested by Newson and Newson (2000). Used with permission from Sage Publications

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Channel and floodplain features. Channel features that contribute significantly to habitat quality and diversity include bedforms, bars, islands, banks, riparian margins, confluences and diffluences. For example, confluences are sites of energy concentration where large-scale turbulence is generated, areas of local acceleration and deceleration are found, sediment sorting is vigorous and large wood tends to accumulate. Unsurprisingly, confluences have been found to be both ecological hotspots (Benda *et al.*, 2004) and places where ecological communities shift (Rice *et al.*, 2001). Multi-channel streams (i.e. braided, anastomosed or meandering streams with wide point bars and chute channels) have numerous confluences capable of contributing habitat and ecosystem benefits similar to those found relatively infrequently at tributary junctions in single-thread streams.

Other particularly important geomorphic attributes include in-stream sediment storage and the proportion of the bankline that is accreting, stable or unstable, which have major implications for avifauna. These attributes, and their contributions to habitat and ecosystem benefits, are altered by the morphological adjustments associated with channel response to disturbance.

Significant floodplain attributes include the extent and connectivity of inundation surfaces, side channels and wetlands. It is difficult to overstate the importance of floodplain extent and connectivity to sediment storage, carbon sequestration and nutrient processing (particularly denitrification). Floodplains have also been demonstrated to increase biocomplexity (Amoros and Bornette, 2002), and fish particularly benefit from floodplain rearing (Henning *et al.*, 2006; Jeffres *et al.*, 2008) in connected channel–floodplain systems.

The significance of access to off-channel aquatic and wetland habitats has been further illustrated with reference to ephemeral floodplain tributaries (Hartman and Brown, 1987), periodically flooded morphological features such as alcoves and backwaters (Bell *et al.*, 2001), seasonally closed estuary lagoons (Hayes *et al.*, 2008) and even artificial water bodies such as gravel pits (e.g. Roni *et al.*, 2006) where, for example, salmon have been shown to grow faster than in even the best 'in-channel' habitats. This led Bond *et al.* (2008) to conclude that access to off-line habitats, although available only seasonally, provides population-scale benefits to salmon by increasing the numbers of juvenile fish that reach the size threshold for marine entry, ocean growth and survival, in time elevating the numbers of fish that return as adults.

Substrate. Both the size and spatial distributions of substrate are important aspects of the channel that are controlled by erosion, transport and deposition processes of sediment. Sediment sorting is particularly significant in coarse-bedded streams, for two reasons. First, selective entrainment and hiding alter the mobility of different size fractions to generate the bed armouring that is vital to macro-invertebrate and spawning habitats. Second, self-organization of moving grains by size creates clusters and patches of differentially sized substrate (Brayshaw *et al.*, 1983), providing homes to a range of benthic organisms with different habitat requirements. Substrate size and sorting also interact with broader-scale hydraulic diversity and sediment dynamics, with the result that bed sediment sizes vary widely between, for example, the head and the tail of bars and the upstream and lee sides of log jams.

Substrate characteristics have been shown not only to be highly responsive to changes in the balance between sediment supply and local transport capacity but also to strongly influence morphological evolution through the impacts of fining and coarsening on flow resistance and bed mobility (Simon and Thorne, 1996). Thus, changes in substrate sorting and patchiness are associated with the evolutionary stages in disturbed channels in ways that are highly significant to habitat and ecosystem benefits.

Vegetation

Multiple attributes of aquatic, emergent, riparian and floodplain vegetation influence fluvial processes, channel morphology, stream functions and hence the quality and diversity of habitat. Vegetation that provides cover from predators, moderates water temperature by shading and stabilizes banks through root reinforcement may be removed during channelization or operational maintenance, or undermined by incision or widening. It follows that loss of vegetation, particularly during Stages 2–6 in the SEM because of scale, has the potential to degrade, compromise or eliminate a significant proportion of the pre-disturbance habitat and ecosystem benefits provided by vegetation.

Metrics used to represent the contribution of vegetation to habitat and ecosystem benefits include the presence of plants (aquatic, emergent, riparian and floodplain) together with two further vegetative attributes: leaf litter production and tree trunk recruitment to the fluvial system. The former supports primary production and hence the trophic status of the watercourse, whereas the latter contributes indirect benefits through cycling nutrients and carbon, generating hydraulic and morphological diversity, promoting channel stability and sediment storage capacity, enhancing substrate sorting and patchiness, and driving shallow hyporheic flow.

Riparian succession is an important attribute whose processes depend on channel migration and/or evolution that topples climax communities and provides opportunities for pioneer species and developing assemblages to create new habitats that contribute fresh ecological benefits. However, realization of the benefits of plant successions depends on the rate of colonization being able to match the pace at which existing assemblages are removed (Shafroth *et al.*,

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2002), which is diminished during the more destructive stages of disturbed channel evolution.

Habitat and ecosystem benefits

The natural ecological functioning of rivers is related to hydromorphological complexity through provision of habitat (Newson and Newson, 2000), and Thorp *et al*. (2010) identified that most natural benefits increase with physical complexity, peaking in streams featuring network channels (i.e. with anabranching or anastomosing network planforms). The attributes selected to represent habitat and ecosystem benefits are described in the following sections under the general headings of habitat, water quality, biota and resilience. Table III details the unique habitat and ecosystem benefits attributed to each stage of the SEM.

Habitat. Refugia from hydrologic extremes (flood and drought) are important to the persistence of habitat and ecosystem benefits. For example, fish will not persist in a reach without refuge from high velocities, intense turbulence and elevated turbidity during floods. Typical refugia include marginal deadwaters, back channels and off-line habitats such as side channels, oxbows and wetlands that are accessible during floods. Flood refugia may form at a variety of scales ranging from the lee of a piece of in-stream wood (small) to hydraulically rough bar tops (medium), to hydraulically connected floodplains (large). Confluences and diffluences also provide flood refugia because one channel usually carries the majority of the flow and sediment, whereas fauna can easily access calmer and clearer water in the other.

Drought refugia depend on the existence of morphological features such as deep pools and scour holes that are hydrologically connected to the hyporheic and groundwater zones. Typically, drought refugia are provided by free pools found at bends and branch confluences, in streams with well-developed pool–riffle sequences, and by forced pools downstream from rock outcrops, log jams and tributary junctions. It follows that the existence of flood and drought refugia, and the ease with which aquatic animals can access them, depend on the hydrologic, hydraulic, morphologic and vegetative attributes of the stream, which are strongly influenced by the stage of evolution.

The presence of exposed tree roots was also identified as providing significant habitat and ecosystem benefits because they fulfil multiple needs, for a range of animals, during various life stages (Raven *et al*., 1998). For example, exposed roots slow velocities and dampen turbulence while providing cover from predators and shade from direct sunlight, attributes functioning over a wide range of flows.

Water Quality. Water quality is a fundamental attribute of habitat and ecosystem benefits. The metrics selected to represent it are clarity, temperature and nutrient cycling.

Water clarity is decreased by turbidity due to high concentrations of total suspended solids. High total suspended solid concentrations are associated with reach-scale channel instability that generates elevated loads of fine sediment derived from local and upstream bed scour and bank retreat, together with the excessive concentrations of fine organic matter that result from the widespread destruction of vegetation in and around unstable reaches, in addition to loading from upstream lakes and wetlands.

The ranges of many aquatic species are limited by water temperature, especially during droughts and summer dry periods (Poole and Berman, 2001) when their survival depends on base flows fed by seepage of relatively cool, clear water from groundwater and/or spring-fed tributaries, coupled with shade that limits direct sunlight from warming stream water during daylight hours (Nielson *et al*., 1994; Baxter and Hauer, 2000).

Whereas external factors control the net flux of heat to the stream, the presence or absence of deep pools connected to the hyporheic zone affect how water temperatures respond (Triska *et al*., 1989; Poole and Berman, 2001). As the exchange of water between the hyporheic zone and the stream is influenced by substrate, bed topography and channel pattern (Poole and Berman, 2001), temperature response is heightened during the early and middle stages of stream evolution.

Nutrient cycling is vital to the stream environment and the ecosystem it supports (Hynes, 1983). Nutrient processing is heavily influenced by stream velocity, exchange between the stream and the hyporheic zone, and the capacity of aquatic and riparian sediment bodies and vegetation to store and release nutrients. It follows that the capacity of the stream to cycle nutrients effectively increases with the extent of the wetted area relative to the flow and the degree to which it is hydrologically connected to the floodplain, hyporheic zone and groundwater, all of which are evolutionary stage dependent.

Biota. According to Newson and Newson (2000), 'it is a valid working principle in ecology that diversity of habitat, if it can be described, paves the way for predictions of the potential diversity of biota.' This principle is complimented by the Riverine Ecosystem Synthesis model developed by Thorpe *et al*. (2006), which predicts that biodiversity, system metabolism and many other functional ecosystem processes are enhanced by habitat complexity at the valley-to-reach scale and which proposes that biocomplexity should be related to hydrogeomorphic complexity. This is the case because habitat diversity and niche availability increase with

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the diversity of channel and flow conditions. Ward and Tockner (2001) suggested that it is hydrological connectivity that controls biodiversity at the floodplain scale, and they concluded that overall biodiversity peaks at intermediate levels of connectivity. Thorp *et al.* (2010) capture this succinctly, noting that 'Biodiversity, as measured by species richness and trophic feeding diversity, is usually greater in physically complex [reaches] (Roach *et al.*, 2009) because habitat diversity is greater and opportunities for both fluvial and floodplain specialists abound (Galat and Zweimüller, 2001).' In interpreting how habitat and ecosystem benefits vary between stages in the SEM, these findings suggest that biodiversity (expressed through species richness and trophic diversity) is a representative biotic attribute that should vary in relation both to the morphological diversity of the channel and the extent and frequency of floodplain connectivity.

The proportion of native plant species is another biotic attribute relevant to evaluating the ecosystem benefits provided by the stream and how benefits vary as the stream evolves. Stages that involve channelization, incision or rapid widening destroy established assemblages and provide opportunities for invasive species to colonize eroding stream banks, retreating terrace edges and accreting berms during the middle stages of channel evolution. Theoretically, native species should be better adapted to the more natural conditions recovered during the latter stages of the SEM (Rey Benayas *et al.*, 2009), and they should, therefore, have a competitive advantage over invasive species, although this is by no means certain.

The foundation for a rich and robust ecosystem lies in first-order and second-order productivities, selected as the third biotic attribute in this evaluation. Thorpe *et al.* (2010; 70) note that '[Reaches] with a greater range of current velocities and substrate types offer habitat niches for a greater diversity and potential productivity of algae and vascular plants.' It follows that productivity is in proportion to the hydrological, hydraulic, morphological and vegetative diversity of the stream.

Resilience. It is vital that the habitat and ecosystem benefits provided by the stream persist over the periods necessary for flora and fauna to become fully established, and this depends on their life cycle and resilience. To be considered resilient, habitat and ecosystem benefits must be able to withstand disturbance in general, and floods and droughts in particular. Hence, in evaluating habitat and ecosystem benefits, resilience is represented by these attributes.

Disturbance to the fluvial system may occur at the catchment, reach or local scales and may result from a wide range of events and activities that affect the flow regime, the sediment regime or the boundary characteristics of the channel (Thorne *et al.*, 2010). Drivers of catchment-scale disturbance include climate change (temperature, precipitation, rain–snow partitioning), land-use change (urbanization, deforestation, afforestation, agricultural intensification, farm abandonment), wild fires, volcanic eruptions and seismic events. Reach-scale disturbances may result from natural events (e.g. base level and valley slope changes due to neotectonics, beaver introduction, or vegetation changes due to infestation and die back) or anthropogenic impacts associated with capital works and/or operational maintenance for a variety of purposes (including flood control, land drainage and navigation).

Generally, disturbance to the habitat and ecosystem benefits provided by the affected reaches depends on the type and extent of morphological response. In reaches that have adjusted naturally to the prevailing flow and sediment regimes, responses are distributed between the nine degrees of freedom that an alluvial channel can change (Hey, 1978). This allows dynamically adjusted streams to remain in meta-stable equilibrium, so that they absorb disturbances while continuing to provide pre-disturbance habitat and ecosystem benefits. Conversely, in reaches that are unstable or which are constrained artificially, responses are focused in fewer of the degrees of freedom (Hey, 1978), which focuses and amplifies the morphological responses to disturbance so that habitat and ecosystem benefits are degraded or destroyed. These characteristics of response to disturbance have been considered in evaluating resilience as a function of channel evolution.

It has long been recognized that disturbance by flood events is essential to support biocomplexity (Junk *et al.*, 1989) and natural hydrological patterns feature prominently in the RAS model of Thorpe *et al.* (2006). However, floods that are amplified by catchment changes, mistimed due to manipulation of the hydrological regime or constrained within constructed or incised channels may not benefit biota, especially native species that are adapted to the frequency, duration and seasonality of natural events.

With this background, resilience to floods becomes important to the on-going delivery of habitat and ecosystem benefits. The severity of flood impacts is largely related to the availability of floodplain space where the stream can diffuse and store flood flows. Consequently, channelization and incision reduce resilience during the middle Stages 2–6 of the SEM because the channel is isolated from its floodplain and floods are confined to a reduced area, exaggerating negative impacts on channel morphology and sediment dynamics and reducing the extent and accessibility of refugia. These effects are partially reversed during late-stage evolution when a new (proto) floodplain develops within the incised canyon, although resilience cannot fully recover to its pre-disturbance level unless the channel aggrades sufficiently that it reconnects with an original

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floodplain that is, itself, still capable of functioning hydrologically and geomorphologically.

Drought resilience is primarily governed by the existence of deep pools fed by perennial flow from groundwater and/or spring-fed tributaries, coupled with the ameliorating effects of shading and connectivity with an extensive hyporheic zone. That said, ephemeral channels can still support rich and diverse ecosystems provided that aquatic and amphibious fauna are suitably adapted and have access to proximal subsurface drought refugia, although deeply desiccated reaches will require recolonization by primary and secondary biota, which lengthens recovery times. It follows that instability that scours or clogs bed sediments, reduces morphological diversity and destroys in-channel and riparian vegetation will reduce drought resilience.

EVALUATION OF STREAM ATTRIBUTES AND HABITAT AND ECOSYSTEM BENEFITS

The physical and vegetative attributes associated with each of the eight stages in the SEM are evaluated in Table II, whereas the habitat and ecological benefits are evaluated in Table III. On the basis of the evaluations set out in Tables II and III, scores were assigned to the attributes and benefits associated with each SEM stage according to an ordinal scale where 3 = abundant and fully functional, 2 = present and functional, 1 = scarce and partly functional, and 0 = absent or dysfunctional.

The scores for each stage in the SEM are listed in Tables IV and V, together with the sums for each SEM stage compared with the maximum possible score. The results are illustrated in Figure 6.

Table IV. Scores for the physical and vegetative attributes for each stage in the Stream Evolution Model. Scores are based on an ordinal scale where 3 = abundant and fully functional, 2 = present and functional, 1 = scarce and partly functional and 0 = absent or dysfunctional

Hydrogeomorphic Attributes Table

Stage	0	1	2	3	3s	4	4-3	5	6	7	8
Physical Channel Dimensions											
Wetted Area Relative to Flow	3	2	1	1	1	0	0	1	1	2	2
Shoreline Length and Complexity	3	2	1	1	1	0	0	1	1	2	2
Channel and Floodplain Features											
Bedforms and bars	2	3	1	0	0	1	0	2	3	3	2
Islands	3	1	0	0	0	0	0	0	0	1	3
Local Confluence/Diffluences	3	1	0	0	0	0	0	0	0	1	3
Stable banks	3	2	2	2	2	0	0	1	2	2	3
River cliffs	2	2	0	1	2	2	2	2	1	2	2
Riparian Margins	3	2	1	1	1	0	0	1	2	2	3
Floodplain Extent and Connectivity	3	3	1	0	0	0	0	1	2	2	2
Side channels	3	2	0	0	0	0	0	0	1	2	2
sediment storage	3	2	1	0	0	0	0	0	1	2	3
Connected Wetlands	3	2	1	0	0	0	0	0	0	1	2
Substrate											
Substrate Sorting	2	3	0	0	1	0	0	1	1	2	2
Substrate Patchiness	3	3	0	0	1	0	0	1	2	3	3
Hydraulics											
Hydraulic Diversity	3	2	0	0	1	0	0	1	1	2	3
Marginal Deadwater	3	2	0	0	0	0	0	0	1	2	3
Vegetation											
Aquatic plants	3	2	1	0	0	0	0	1	2	2	3
Emergent Plants	3	1	1	1	1	1	0	2	2	1	3
Riparian plants	3	2	0	0	1	0	0	1	1	2	3
Floodplain plants	3	3	2	0	0	0	0	0	1	2	3
Woody debris	3	1	0	1	1	2	1	2	2	1	3
Leaf litter	3	2	0	1	2	0	0	1	2	2	3
Hydrological Regime											
Flood pulse	1	1	2	3	3	3	3	2	2	1	1
Flood attenuation	3	2	1	0	0	0	0	0	1	2	3
Base flow	2	3	1	0	0	0	0	0	1	3	2
Hyporheic connectivity	3	3	2	0	0	0	0	1	2	3	3
Results											
possible	78	78	78	78	78	78	78	78	78	78	78
sum	72	54	19	12	18	9	6	22	35	50	67
ratio	92%	69%	24%	15%	23%	12%	8%	28%	45%	64%	86%

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Table V. Scores for the habitat and ecosystem benefits for each stage of the Stream Evolution Model. Scores are based on an ordinal scale where 3 = abundant and fully functional, 2 = present and functional, 1 = scarce and partly functional and 0 = absent or dysfunctional

Habitat and Ecosystem Benefits Table

Stage	0	1	2	3	3s	4	4-3	5	6	7	8
Habitat											
Flood Refugia	3	2	0	0	0	0	1	1	1	2	2
Drought Refugia	2	3	0	0	0	0	0	0	1	3	2
Exposed tree roots	3	1	0	1	1	1	0	0	1	1	3
Water Quality											
Clarity	3	2	1	0	0	0	0	1	2	2	3
Temperature amelioration (shade and hyporheic flow)	3	3	1	1	2	0	0	1	2	3	3
nutrient cycling	3	2	1	0	0	0	0	1	1	2	3
Biota											
Biodiversity (species richness and trophic diversity)	3	2	0	1	1	1	1	1	1	2	3
Proportion of Native Biota	3	2	1	1	1	1	1	1	1	2	3
1st and 2nd Order Productivity	3	2	1	1	2	1	0	1	2	2	3
Resilience											
Disturbance	3	3	1	0	1	0	0	1	1	2	2
Flood and Drought	3	2	0	0	1	0	0	1	2	1	2
Results											
possible	33	33	33	33	33	33	33	33	33	33	33
sum	32	24	6	5	9	4	3	9	15	22	29
ratio	97%	73%	18%	15%	27%	12%	9%	27%	45%	67%	88%

Physical and vegetation attribute scores are highest (92%) for Stage 0 streams (pre-disturbance, anastomosing network) but fall to a low of just 8% for streams in the Stage 4-3 short-circuit (degraded with renewed incision). Stage 8 streams provide the second highest scores, reflecting stream recovery to something near its pre-disturbance (Stage 0) configuration. However, whereas in Stage 8 the stream possesses all the physical and vegetative attributes and provides the full range of the ecosystem benefits present in Stage 0 (i.e. its pre-disturbance condition), Stage 8 scores are somewhat lower because the stream system is smaller; it is inset into a narrower functional floodplain.

Scores for the early and late stream Stages (0, 1 and 7, 8), where floodplain attributes and processes are prominent, are distinctly different from those Stages in-between (2 to 6). The most abrupt change in stream attributes and benefits is the precipitous decline in both that occurs between Stages 1 and 2 because of the direct effects of channelization and Stage 3 when incision disconnects the channel from its floodplain.

A hysteresis loop is revealed when benefits scores are plotted as a function of the stream's hydrogeomorphic attributes (Figure 7). It is apparent that the habitat and ecosystem benefits provided by streams recover less quickly, and less completely, following disturbance than do the corresponding hydrogeomorphic attributes. Over short time scales, the loop is likely broader because of delays in colonization and the cumulative effects in physical and ecological processes common to disturbed catchments.

DISCUSSION AND IMPLICATIONS OF THE STREAM EVOLUTION MODEL FOR RIVER MANAGEMENT AND RESTORATION

The SEM advances the lasting value of the CEMs originated by Schumm *et al*. (1984) and Simon and Hupp (1986). It builds on these models, taking advantage of advances in knowledge and improved understanding of process-response mechanisms and links between morphology, habitat and ecosystem benefits made during the quarter century since they were conceived. This is done by redefining the pre-disturbance and post-recovery morphologies, replacing linear progression with an evolutionary cycle, broadening the scale to consider streams in their catchment rather than simply as incised channels and linking habitat and ecosystem benefits to physical attributes and system responses to disturbance.

In common with the original CEMs, the SEM offers users interested in system-wide processes rather than reach-specific morphological characteristics the opportunity to undertake *space-for-time* substitution. In essence, this

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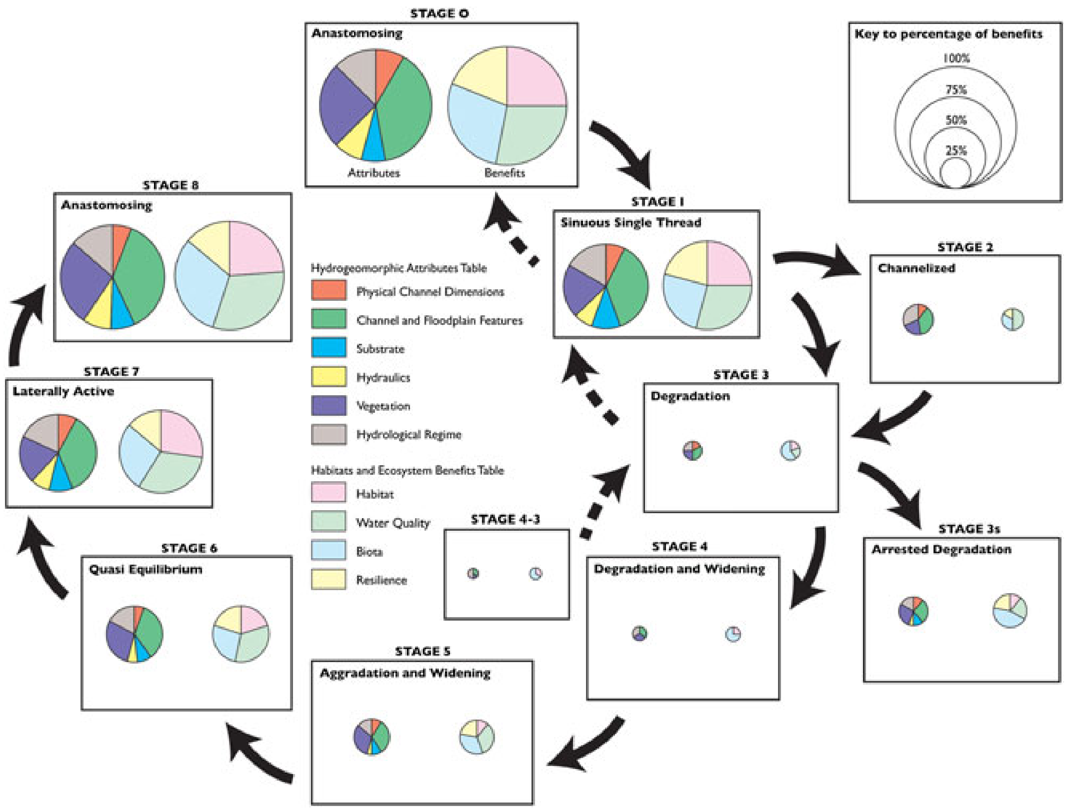

Figure 6. Habitat and ecosystem benefits provided in each stage of the Revised Channel Evolution Model. Each stage is represented by two pie charts whose diameters signify the relative percentage of maximum benefits as tabulated in Tables IV and V. For each stage, the pie chart on the left summarizes the richness and diversity of the hydromorphic attributes, whereas the pie chart on the right summarizes the associated habitat and ecosystem benefits

involves replacing the time dimension in the model with distance from disturbance. When the SEM is considered in the catchment context (Figure 8), what emerges immediately is the value of conserving or restoring the processes that characterize sediment transport at the reach scale. For example, mid-catchment basins moderate sediment delivery events or elevate prolonged loads and therefore buffer sediment impacts to more responsive downstream reaches. If sediment exchange reaches are turned into sediment transfer reaches by channelization, flood control projects, or widespread bank revetment, downstream sediment loads and calibres will increase, transmitting disturbances downstream that could have been moderated upstream and risking overwhelming the capacities of lowland channels, riparian zones, floodplains and associated wetlands to assimilate sediment without damaging those relatively more valuable reaches. Sediment accumulation in mid-catchment fans or alluvial basins is the natural process by which sediment pulses are processed in naturally functioning catchments. This process not only ameliorate the impacts of coarse sediment delivery in lowland reaches downstream but also provides the mechanism by which Stage 1 or 7 streams may attain the networks representative of Stage 0 or 8 that result in comparatively greater ecological benefits. More generally, Figure 8 reminds end-users that stream evolution pathways and habitat outcomes depend on the position within the catchment as well as the type and severity of the disturbance.

The SEM provides a lens for viewing reach-scale interventions (such as widespread bank stabilization intended to manage sediment, sometimes considered a pollutant in regulatory policies) when catchment-scale problems are the root cause of elevated sediment loads (Doyle and Shields, 2012; Hupp *et al*., 2013). The SEM not only helps to identify the possible unintended consequences of invoking these actions but also indicates the potential value of re-activating sediment exchange and storage functions in mid-catchment alluvial reaches that can buffer the more sediment-sensitive reaches downstream, while transforming single-thread, meandering channels into more ecologically valuable channel networks. This re-emphasizes the importance of longitudinal and lateral connectivity in the sediment system and the disproportionate risks of disconnecting alluvial streams from sediment sink and source processes (i.e. floodplain).

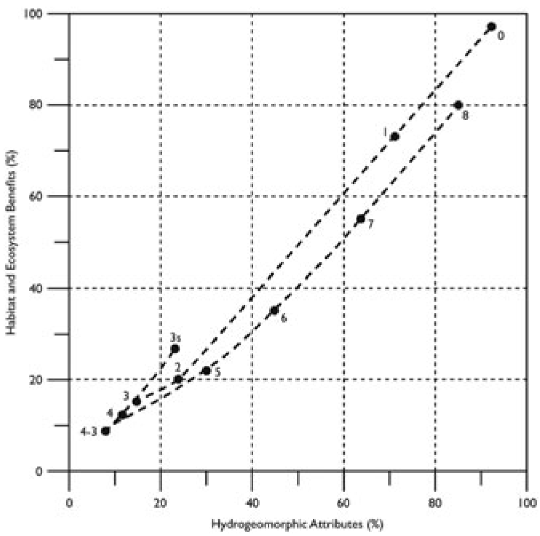

Figure 7. Plot of habitat and ecosystem benefits as a function of hydrogeomorphic attributes, from Tables IV and V. There are generally two fields, streams that have greater than 50% of the hydrogeomorphic attributes and habitat and ecosystem benefits, and streams with less than 30%, while Stage 6 streams are intermediate. The most abrupt difference between adjacent stages is from 1 to 2, where scores drop from nearly 75% to less than 25% in constructed channels, primarily because of floodplain disconnection. A hysteresis loop reveals that habitat and ecosystem benefits recover less quickly and less completely than do the corresponding hydrogeomorphic attributes over long time scales, and likely, the loop is broader over short times scales

The SEM differs from its CEM predecessors in being expressed as a *cycle* rather than a linear succession of morphological states and adjustments. This recognizes that vertical adjustments, lateral changes, and channel instability and recovery often occur cyclically, with multiple episodes of channel degradation/aggradation, widening/narrowing and enlargement/shrinkage being generated through complex response to a single external disturbance or the crossing of one or more internal, geomorphic thresholds. The result is for late-stage morphologies to be nested within the boundaries of channels produced by earlier evolutionary stages, although a valley-fill cycle may result in a larger and richer end-stage network.

The SEM also recognizes that local and site-specific conditions may cause short-circuits in the cycle with, for example, repeated cycles of degradation. Similarly, the expected sequence of post-disturbance evolution may be arrested by natural controls (e.g. geologic or vegetation), or reversed by new disturbances (e.g. sediment pulses or afforestation), or perpetuated by management interventions. These processes turn what would otherwise be transitional stages into longer term configurations and limit recovery of habitat and ecosystem benefits.

Making strategic and cost-effective river management decisions has never been more important, as stresses on aquatic systems will increase as human demands for land and water rise. It is now recognized that fluvial functions are fundamental to the generation of natural capital and providing the ecosystem services upon which civilization depends. It is also accepted that past efforts to channelize and minimize rivers have depleted natural capital and

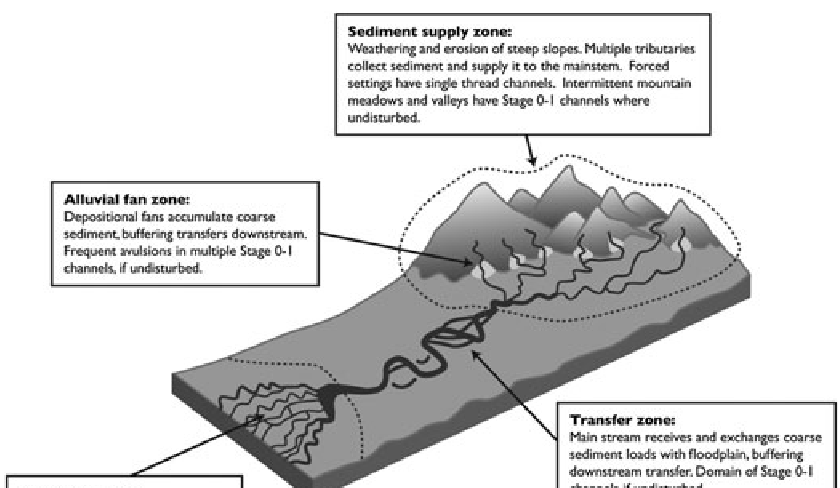

Figure 8. Process domains in the fluvial system associated with the Revised Channel Evolution Model. Domains in a river basin can be generally characterized as governed by supply, exchange/transfer or deposition of sediments. Channelization or embankments in the Alluvial fan and Transfer zones diminish beneficial sediment deposition processes and artificially promote downstream transfer of coarse sediment and compromise habitats less resilient to increased sediment loads

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severely damaged ecosystem services overall. Globally, many alluvial systems that formerly exchanged sediment freely with their floodplains are now levee confined, channelized and incised. In their earlier condition, these rivers could accept, store and exchange periodic heavy floods and inputs of sediment and nutrients generated by disturbances upstream, such as widespread land sliding triggered by extreme rainfall, wildfires and even volcanic eruptions; and buffering downstream depositional reaches from excessive, coarse sedimentation and other impacts. The result of the past and continuing emphasis placed on flood control, land drainage and property stability has been to sensitize fluvial systems to sediment disturbances and systemic imbalances. Elimination of sediment deposition and exchange processes from basins makes the downstream environments vulnerable to damage by singular events and less resilient to chronic impacts of climate and land-use changes.

River restoration efforts typically focus on the geometry of channels with the goals of reducing and then balancing sediment loads at the reach scale, effectively attempting to turn every reach into a sediment transfer zone. This perpetuates an erroneous approach to management of the alluvial channel system and may partially explain why the regeneration of high-quality habitat remains limited (Doyle and Shields, 2012) and restoration of freshwater ecosystems remains elusive (Bernhardt and Palmer, 2011): the channels in most alluvial reaches are *restored* to forms equivalent to Stages 3–6 in the SEM. These relatively low value forms are then preserved through stabilization measures. Even though using soft engineering and natural materials such as biotechnical revetments and large wood has become common, stabilization impedes the fluvial processes that could drive continued evolution to the substantially more resilient and valuable Stages 7 and 8.

The implications for river management that stem from the SEM are that stabilizing channels in Stages 2 to 5 is not only costly (requiring maintenance) and risky (places people and property in hazardous locations) but also ecologically counterproductive. Restoring streams to Stage 6 is also a relatively ineffective strategy because without floodplain, they are largely non-deformable and less resilient to future catchment disturbances. Acceleration of natural evolution by intervening to move the channel forward through the cycle to Stage 7 or even 8 is suggested, or strategically planning for a deformable Stage 6 that can suitably respond to a future catchment disturbance event such as dam removal. Where Stage 0-1 or 7-8 channels exist, maintaining existing or enhancing degraded sediment deposition zones upstream would be a valuable long-term conservation strategy. While the advantages of a channel network in terms of moderating sediment transfer, promoting sediment exchange and enhancing the sediment processing functions offered by the active floodplain of an alluvial valley are well established and ecologically superior, constraints imposed by development and/or infrastructure may complicate, delay or prevent this as a restoration goal.

The decision to aim for single-thread, active meandering (Stage 7) or prompted recovery of an anastomosing channel network (Stage 8) will be constrained by space that can be made available for lateral migration and stream evolution. ‘Passive restoration’ through ceasing periodic de-silting and maintenance of Stage 2 channels can rapidly transform to a Stage 7 (active meandering) or 8 (an anastomosed network), provided floodplain space is available or obtained through strategic retreat.

The arguments advanced here concerning sediment processes in the middle reaches of incised alluvial basins are just one example of how the SEM could be used to provide a framework for improved catchment management and decision making in river restoration. Aligning management and restoration objectives with SEM stages and evolutionary trends can promote rather than counteract natural processes. Adopting stream management approaches that enhance natural evolution require more space than those set on impeding it, but they hold the promises of increasing biodiversity, promoting recovery of endangered species, improving the resilience and sustainability of ecosystem services both in the restored reach and those downstream, optimizing climate resilience, minimizing risks to property and human safety, and maximizing returns on restoration investments.

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