A Channel Evolution Model to Guide Sustainable Urban Stream Restoration

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Channel evolution models (CEMs) are used to structure the interpretation of observed channel morphology to support long-term restoration of these systems. However, channels reflect the variety of their watersheds' climatological, ecological and physiographic contexts, and so no single CEM can be truly 'global'. Unrecognized differences between the assumptions and the reality of evolutionary trajectories of particular streams can subsequently lead to restoration actions that neither fully achieve their intended objectives nor successfully self-maintain even limited improvements. Despite the daunting variety of biophysical settings, however, urbanization imposes distinctive, homogenizing influences on virtually all watercourses, suggesting that even a relatively small set of evolutionary pathways can embrace much of the diversity of critical watershed drivers on urban channels. CEMs describing single-thread channel response to incision are most common in the published literature, but not every urban disturbance yields this classic sequence, initiated by excess transport capacity followed by incision, bank erosion, widening and ultimately a lowered re-equilibrated channel. A comprehensive urban CEM must also include responses under less common (but locally ubiquitous) conditions, such as excess sediment relative to transport capacity (the 'inverse' of the classic CEM), imposed constraints on vertical and/or lateral adjustment, and multi-thread channels or those influenced by instream or riparian vegetation. An urban CEM also requires a hierarchical framework that acknowledges fundamental differences in the process drivers within any given watershed, because a single observation of channel form can rarely pinpoint the context or evolutionary trajectory of every stream. We present a geomorphic framework for diagnosing and predicting the evolution of urban streams, potentially guiding the selection of restoration targets that are achievable within an urban context and sustainable without ongoing maintenance.

Key words: *urban streams, channel evolution models, restoration, sustainability, geomorphology*

Introduction

Modifications to the land surface during urbanization impose fundamental changes on runoff-generating processes. Because infiltration capacities of covered or compacted areas are reduced to near-zero, overland flow is introduced into areas that formerly may have generated only subsurface runoff (Leopold 1968). Urbanization also affects the drainage system more directly. Gutters, drains and storm sewers convey surface runoff rapidly to stream channels; once-natural channels downstream may be straightened, deepened, isolated from their floodplains, or lined with concrete. A dramatically altered hydrograph results, including higher downstream flood peaks (Hollis 1975) and rapidly varying discharges, with widespread effects on both the channel and its instream biota (Walsh *et al*. 2005).

Changes to channel morphology are among the most common effects of urban development on natural streams, resulting from both direct modification and the more pervasive effects of increased discharge (Booth and Henshaw 2001; Gurnell *et al*. 2007; Chin *et al*. 2013). These morphologic changes are the focus here because of their ease of observation and historical utilization for diagnosing stream-channel conditions. However, regulatory drivers and social concerns now commonly concentrate less on geomorphology and more on biota, whose presence and health depend on complex interactions of not only physical but also chemical and biological processes (Figure 1). Thus, this emphasis on channel morphology is more 'diagnostic' than 'mechanistic' – although some biological impacts are a direct consequence of morphologic change, they are primarily a consequence of multiple altered water resource features, of which hydrology is typically the most pervasively changed in an urban watershed, but morphology is most easily observed.

Emphasizing channel morphology (the 'habitat structure' of Figure 1) reflects not only its ease of observation and measurement but also its common manipulation by stream-restoration projects. Given this attention, it is also the feature most urgently in need of sustainable approaches to restoration – meaning those actions that can achieve human goals while supporting landscape- specific ecological services (Wu 2013), and that will con- tinue to function with minimal or no further intervention. This requires integrating spatial and temporal *contexts* into the identification, scoping and design of stream restoration projects, using a hierarchical framework to interpret stream-channel form as a result of urbanization. Figure 1 emphasises that no one feature limits biological condition; conversely, improving any one feature does not guarantee corresponding improvement in biology. Thus, the intentionally limited focus of this discussion does not provide a complete roadmap for achieving sustainable restoration, but it does describe one of the necessary components.

Approach

Successful restoration requires assessment of the underlying *causes* of degradation, following these key assumptions (Beechie *et al*. 2010; Hughes *et al*. 2014): first, assessment must reflect the hierarchical set of influences on stream channels (Figure 2); second, such influences are not uniform across all watersheds (Brierley and Fryirs 2009), and so prospective restoration efforts should reflect an accurate diagnosis of the underlying cause(s) of identified problems and successful treatments; and third, innumerable interactions are possible between individual channel types and the full suite of anthropogenic stressors, so any workable framework must embrace the simplifying attributes common to most urban streams.

Based on these assumptions we present a frame- work to guide urban stream restoration. It consists of a coarse discrimination of streams based on readily observed form, an urban channel evolution model that incorporates time into otherwise static groupings of channels, and the recognition of alternative channel responses to regionally different watershed processes and attributes.

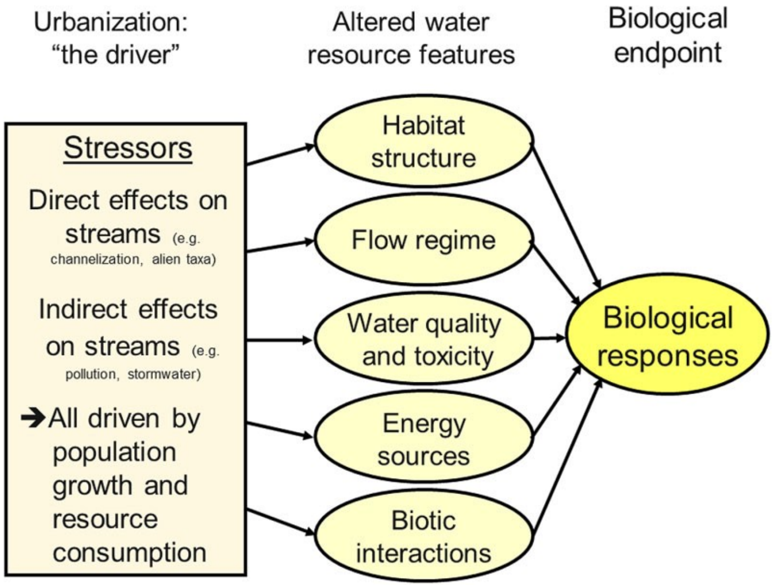

Figure 1 The five water resource features that are affected by urbanization and that in turn determine biological response. Modified from Karr and Yoder (2004)

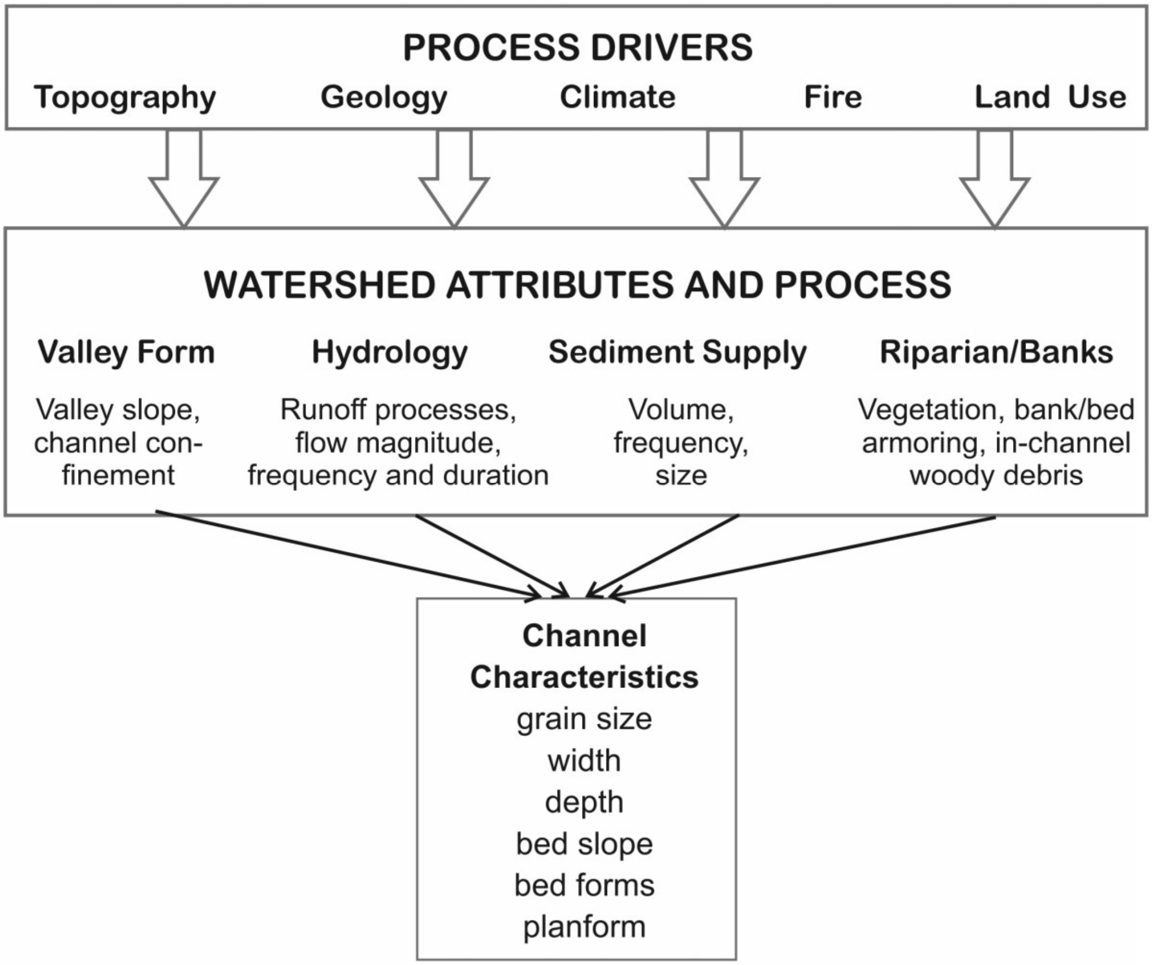

Figure 2 The hierarchical influence of landscape-scale drivers on watershed attributes and processes and, ultimately, on channel characteristics. Modified from Buffington *et al.* (2003)

Channel evolution models

As the term is typically used, channel evolution models (hereafter, CEMs) are idealised depictions of the morphologic stages through which a river or stream channel progresses in response to disturbance. CEMs do not normally reflect short-term adjustments (van Dyke 2013). Instead, these models represent the

> “…discrete phases or stages, each characterized by the domi- nance of particular adjustment processes [that] permit reconnaissance-level interpretation of past, present, and future channel processes.” (Simon and Rinaldi 2006, 368)

The purpose of a CEM is to simplify these stages into a relatively small number of commonly observed states with predictable sequences that, ideally, can be recognized from visual observation of channel form.

The ‘classic model’

Models that describe the response of incising channels are by far the most common in the CEM literature; we collectively term them the ‘classic model’ in recognition of their pervasive, long-standing role in the geomorphic literature. They share the same fundamental sequence:

1 An initial disturbance, causing an imposed imbalance between sediment-transporting capacity and sediment supply, commonly expressed through changes in Lane’s (1955) balance relationship ($Q \cdot S \sim Q_s \cdot D_{avg}$): increased discharge (Q) – from flow diversions, storms,

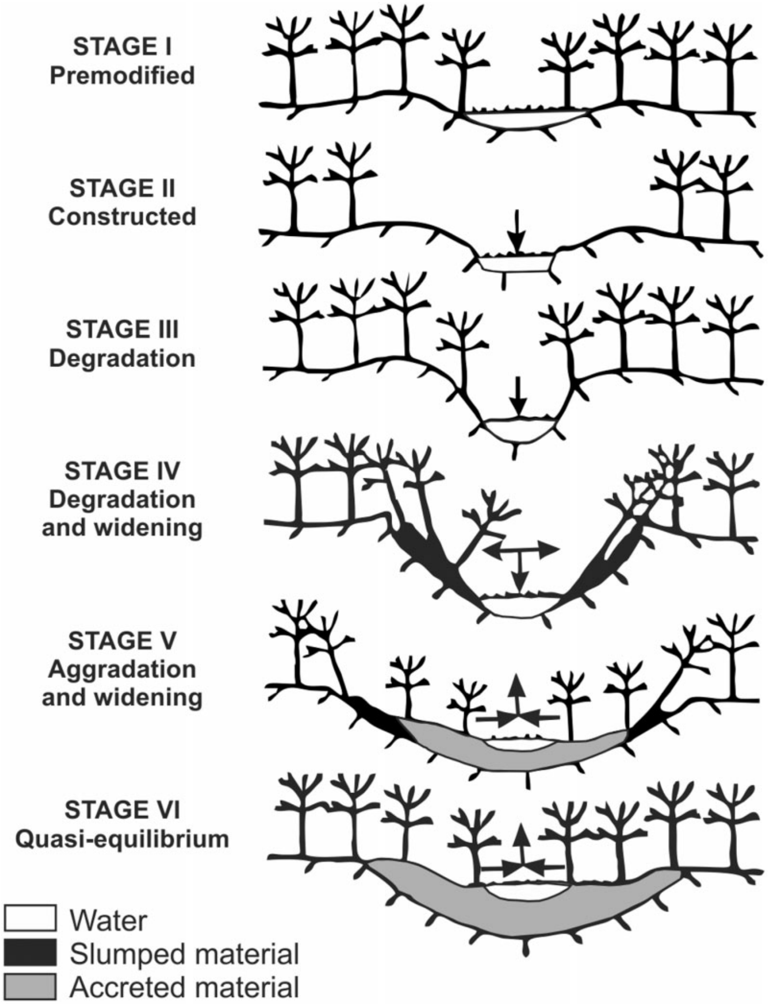

Figure 3 The ‘classic’ channel evolution model. Redrawn from Simon and Hupp (1986)

urbanization; increased slope (S) – from channel straightening, meander cut-offs; and decreased sediment supply (Q_s) – from upland land-surface stabilization, channel armoring, sediment-blocking instream infrastructure. *Increased* sediment supply is also common, but recognized as typically short-lived, and changes to the last of Lane’s variables, average grain size (D_{avg}), are typically identified only as a secondary response.

2 Incision of the channel bed.

3 Mass failure of the channel banks as they become oversteepened and/or exceed a stable height, with consequent channel widening.

4 The reestablishment of a lower, ‘inset’ floodplain/channel system, regarded as the new stable condition.

The most commonly cited CEM was developed for Oaklimeter Creek, an incised stream in northern Mississippi (Schumm *et al*. 1984; Watson *et al*. 1986). This model was initially used to reflect the spatial distribution of channel conditions in response to lowering of the downstream base level, but it has been widely recognized in other settings, particularly those associated with other common disturbances listed above (e.g. Simon and Hupp 1986; Simon 1994; Fryirs and Brierley 2000) (Figure 3).

Other evolutionary trajectories

The range of evolutionary trajectories included in any CEM inevitably reflects a context determined by local conditions rather than the full range of process drivers.

However, many conditions typical of urban watersheds are not emphasized (e.g. Phillips 2013; van Dyke 2013), and not every disturbance results in the sequence described in the classic model, which presumes a single-thread channel that is free to adjust both laterally and vertically (i.e. an 'alluvial' channel). Nonetheless, because this CEM is so widespread in the literature, and commonly the only acknowledged CEM, its implicit assumptions usefully serve as a benchmark for contrasting with other settings.

In particular, not every disturbance to a channel results in a shortage of sediment supply relative to in-channel transport capacity. For example, large natural inputs of sediment, such as from landslides or debris flows, typically result in an alternative evolutionary trajectory of channel widening, aggradation and braiding in originally single-thread systems (Simon 1992; Kondolf *et al*. 2002; Hoffman and Gabet 2007). Although these processes are not common in developed cities, urbanization is widely recognized as a source of short-term increased sediment in channels (Wolman 1967; Gregory *et al*. 1992); zones of upstream channel erosion can also result in significant long-term sediment accumulation in downstream reaches (Booth and Henshaw 2001; Colosimo and Wilcock 2007).

Multi-thread channels also do not align with implicit assumptions of the classic CEM. The simple division into single-thread and multi-thread (or 'braided') channel patterns (Niezgoda and Johnson 2005) usefully subdivides common evolutionary trajectories of urban channels and distinguishes unique evolutionary trajectories in response to disturbance (e.g. Surian and Rinaldi 2003; Hawley *et al*. 2012). Multi-thread channels are relatively uncommon in humid parts of mid-continental North America and are not typically associated with incising streams, and so they are not recognized in the classic CEM or its variants. Their predominance in the semi-arid southwest USA, however, led Hawley *et al*. (2012) to explore evolutionary trajectories in a geographic region characterized by semi-arid climate, high sediment loads and limited influence of riparian vegetation. They found close parallels with the classic single-thread, incised-channel CEM for channels responding to increased flow, lowered base level or channelization. However, they also noted *decreased* sediment loads as a relatively common driver of change in this naturally high-sediment-yielding region (Bledsoe *et al*. 2012), initiating the same morphological sequence as the classic CEM. Cluer and Thorne (2014) suggest that multi-thread channels were once more common prior to widespread human settlements, and that the prevalence of single-thread channels today reflects earlier, widespread anthropogenic impacts that are not recognized by mostCEMs.

Direct channel modifications can also initiate substantial (and typically unintended) responses, of which some but not all are anticipated by the classic CEM. Channel straightening (Simon 1994) and the clearing of in-channel roughness (such as large woody debris) that had been providing a critical degree of energy dissipation (Kaufmann *et al*. 2008) can initiate the classic sequence of incision–widening–inset floodplain and can also transform reach morphology from forced pool-riffle or step-pool to plane-bed (Montgomery and Buffington 1997). Where the primary effect of channel-bank modification is the loss of riparian vegetation, however, channel widening without incision can result from the loss of root cohesion. Depending on the broader context of channel slope, bank slope and the fluxes of water and sediment, this can simply result in a wider single-thread channel or a fully transformed, multi-thread form (Eaton *et al*. 2010).

Non-alluvial channel response

Many urban streams are constrained in one or both of their vertical and horizontal dimensions (i.e. a 'non-alluvial channel'), rendering many of the assumptions of the classic CEM inappropriate. Even where the classic state of transport imbalance exists (i.e. $Q{\cdot}S > Q_s{\cdot}D_{avg}$) and channel deepening and subsequent widening is predicted, external constraints may limit this trajectory. The most common such constraint is a non-erodible bed, whether natural (resistant bedrock) or constructed (e.g. concrete). Vegetation on the bed of the channel, particularly in ephemeral or intermittent channels, can also reduce bed erodibility. Even discontinuous constraints to vertical incision can provide effective reach-scale vertical stability, be they the immobile grains of a (stable) step-pool channel, constructed check dams and grade-control weirs, or simply the elements of urban infrastructure such as pipeline crossings or culverts that provide incidental vertical stability in the course of serving other human needs (Chin 2006). Commonly, however, constructed grade controls are widely spaced, permitting flow–sediment interactions to develop between structures. In such cases, an imposed depositional zone is created upstream, commonly expressed by an aggrading channel (and potentially with locally braided morphology), while a strongly erosive regime exists immediately downstream whose channel does tend to follow, at least locally, the trajectory of the classic incised-channel CEM (Figure 4).

Where incision is constrained, widening is commonly amplified but only if the banks are erodible (e.g. Phillips 2013). Rigid structures that limit channel widening are particularly widespread in the urban environment, however, because they are commonly built in response to (or in anticipation of) the direct encroachment of an eroding stream channel into developed land. Bank stabilization can amplify incision in the absence of grade control. Where all channel adjustment is limited by

Figure 4 Views upstream (left) and downstream (right) of Borrego Canyon (Irvine, CA, USA)
Notes: Reaches are less than 20 m apart, separated by a concrete grade-control structure (partly visible in lower left corner of downstream view). Channel is aggraded and braided upstream, with severe incision immediately downstream

completely static channel boundaries, however, mobile sediment and other obstructions will be swept downstream. Any remaining in-channel material will be limited to either fully immobile elements or fortuitously interlocked clasts or debris that can resist transport in all but the largest of flows (Montgomery and Buffington 1997).

Removal of instream and riparian vegetation also can induce non-alluvial channel responses (Osterkamp *et al*. 2012). Such responses are not addressed by the classic CEM, particularly in those regions where large woody debris is a significant influence on (non-urban) channel form and processes. Large woody debris typically creates temporal variation and spatial complexity in rivers, conditions that can hasten the reestablishment of a stable form and whose absence can preclude that stability altogether (e.g. Wallerstein and Thorne 2004; Curran and Hession 2013).

The urban CEM

Guided by these considerations, an 'urban channel evolution model' is presented, tailored to the range of disturbances and external constraints typical of urban and urbanizing watersheds. Of the many potential disturbances to channels, it emphasizes only a few: the long-recognized increases in the magnitude and duration of erosive flows from watershed development, the direct modification of channel boundaries, and watershed-scale changes to sediment delivery (Table 1). This emphasis does not preclude the myriad other interactions between water chemistry, energy inputs and biota embraced by more comprehensive conceptual models of stream ecosystems (e.g. Walsh *et al*. 2005, their Figure 1). It is intentional, however, because many have observed that the consequences of these changes, particularly that of urban-altered hydrology (e.g. Konrad and Booth 2005; DeGasperi *et al*. 2009), overwhelm all other factors in most geographical, geomorphic and ecological settings.

Using the urban CEM as a predictive tool

In general, any CEM can be used in one of two ways: to *predict* the likely response of a channel to an anticipated disturbance or to *diagnose* the cause of geomorphologic change of a channel that has already been impacted by disturbance(s). As a 'predictive' urban CEM, the current channel form provides an initial classification, and the anticipated disturbance then defines a limited number of alternative future trajectories for channel change in an urbanising landscape (Table 2, Figure 5).

Both flow increases from watershed urbanization and various forms of direct channel modification can result in *channel incision*, the disproportionate (and commonly rapid) downcutting of the channel bed that is the hallmark of the classic CEM. Where the magnitude of change is low, or where unconfined floodplains allow for flow widening without commensurate deepening, flow increases can instead generate more limited *channel expansion*, wherein the channel cross section increases in approximate proportionality to discharge increases (Booth 1990). Other, less common responses to disturbances are varied and can include changing bed-sediment sizes, channel narrowing and aggradation (e.g. Booth and Henshaw 2001; Chin *et al*. 2013; Hawley *et al*. 2013).

Disturbances to multi-thread channels fall into two broad categories: those that induce changes in the size or position of individual channels but without any fundamental shift in planform, and those that cause a shift to a single-thread channel pattern. Hawley *et al*. (2012) recognized primarily the former type of evolutionary trajectory, but the transition from multi- to single-thread channel, not widely reported in natural settings but a common (and sometimes intentional) change in urban areas, has major consequences for both geomorphic and biological conditions (Cluer and Thorne 2014).

Table 1 Attributes of urban watersheds that can initiate channel response

Disturbance and/or other urban conditions	Initial local physical response(s)	Downstream physical response(s)
Direct, urban-specific channel modifications		
1 Channel straightening resulting in an increased slope (↑S; classic CEM)	Incision, bed coarsening, widening	Incision, declining with deposition and/or new intervening sediment inputs. Severe upstream incision may cause significant downstream aggradation with widening/braiding for coarse sediments
2 Reduced roughness (LWD removal, other channel smoothing)	Channel simplification, incision, bed coarsening, widening	Incision, declining with deposition and/or new intervening sediment inputs
3 Channel confinement (levees, other floodplain–channel disconnections)	Incision, bed coarsening	Incision, declining with deposition and/or new intervening sediment inputs
4 Bed armouring, other continuous or discontinuous grade controls	Widening, potential for upstream aggradation and downstream incision below individual grade-control structures	Varied, depending on magnitude of sediment trapping at grade-control structures and/or localised incision and downstream sediment release
5 Bank armoring	If combined with ↑Q: incision, channel simplification, bed coarsening	Incision, declining with deposition and/or new intervening sediment inputs
6 Riparian vegetation removal	Channel widening, with or without incision following the classic CEM due to other disturbances	Minimal response, unless the local widening is severe and downstream sediment delivery is high – then, aggradation
Watershed-scale disturbances		
7 ↑Q (increased discharge – classic CEM)	Incision, bed coarsening, widening	Incision, declining with deposition and/or new intervening sediment inputs. Severe upstream incision may cause significant downstream aggradation
8 ↓Qs (decreased sediment input – common accompaniment to the classic CEM)	Incision, bed coarsening	
9 ↑Qs (increased sediment input – ‘construction phase’ of urban development; also downstream deposition of upstream-eroded sediment)	Aggradation, braiding, widening, bed fining	Downstream response depends on channel attributes
10 Perennial baseflow into once-intermittent streams (surface water and groundwater inputs)	Bed/riparian vegetation growth, conversion from multi- to single-thread channel, narrowing, incision with high flow/vegetation feedback	Same as local

Notes: Symbology from Lane (1955): ‘Q’ = discharge, ‘S’ = channel slope, ‘Q_s’ = sediment discharge. Up arrow indicates an increase in the notated variable; down arrow, a decrease. CEM = channel evolution model; LWD = large woody debris

Table 2 Summary of the urban CEM used as a predictive tool, read from left to right

Channel type	*Anticipated urban disturbance(s)*	*Primary response; other responses/considerations*	
Alluvial, single-thread	Increased Q or decreased Q_s; straightening, reduced roughness	If low-magnitude disturbance: expansion (in both width and depth)	
		If high-magnitude disturbance: incised-channel (classic) CEM, bed coarsening	
	Riparian vegetation removal	Widening	Potential conversion to multi-thread
	Confinement	Incision, bed coarsening	
	Increased Q_s	Aggradation, widening, bed fining	Potential conversion to multi-thread
Alluvial, braided	Increased Q	Incision and/or widening	Potential conversion to single thread; bed coarsening
	Decreased Q_s	Narrowing and/or incision	
	Confinement	Incision	
Non-alluvial: bed-stabilised	Increased Q	Widening, bed coarsening	Braiding/incision may occur above/below intermittent grade control(s)
	Decreased Q_s	Bed coarsening	Incision may occur below grade control(s)
Non-alluvial: bank-stabilized	Increased Q or decreased Q_s	Incision, bed coarsening	Progression of classic CEM depends on magnitude of incision relative to bank protection
Non-alluvial (any)	Increased Q_s	Aggradation, bed fining	

Notes: 'Alluvial' channels are those able to adjust their form and size both laterally and vertically; 'non-alluvial' channels are constrained by natural or artificial structures in one or more dimensions. See Figure 5 for a graphical representation of this application. CEM = channel evolution model; 'Q' = discharge; 'Q_s' = sediment discharge

Using the urban CEM as a diagnostic tool

As 'diagnosis', the urban CEM provides a framework for inferring the likely disturbance(s) from observed conditions in a stream channel that has already partly (or wholly) completed an evolutionary trajectory (Table 3). Using the CEM to guide an inductive approach such as this, however, is limited for two reasons: (1) the same channel form can be associated with more than one type of disturbance, and so observed channel conditions cannot uniquely identify causal drivers and (2) this CEM is explicitly limited to the relatively narrow range of presumptive disturbances common to the urban environment.

Regardless of whether the urban CEM is applied as a predictive or a diagnostic tool, its sole focus on the *geomorphic* expression of disturbance in urban or urbanizing channels renders it a limited but intentionally pragmatic approach for diagnosing causal relationships. Users must recognize, however, that *any* CEM is context-bound, and that broad applicability requires a climate- and physiography-based framework, or at minimum the qualitative recognition of how different settings will render certain relationships more or less likely to be expressed. More detailed 'stream classification' based on channel morphology may be warranted for determining specific restoration targets and implementation strategies (e.g. Niezgoda and Johnson 2005) but is not necessary (nor, likely, appropriate) when first diagnosing the cause and trajectory of the response to an existing disturbance. Lastly, CEMs are commonly used to infer evolutionary

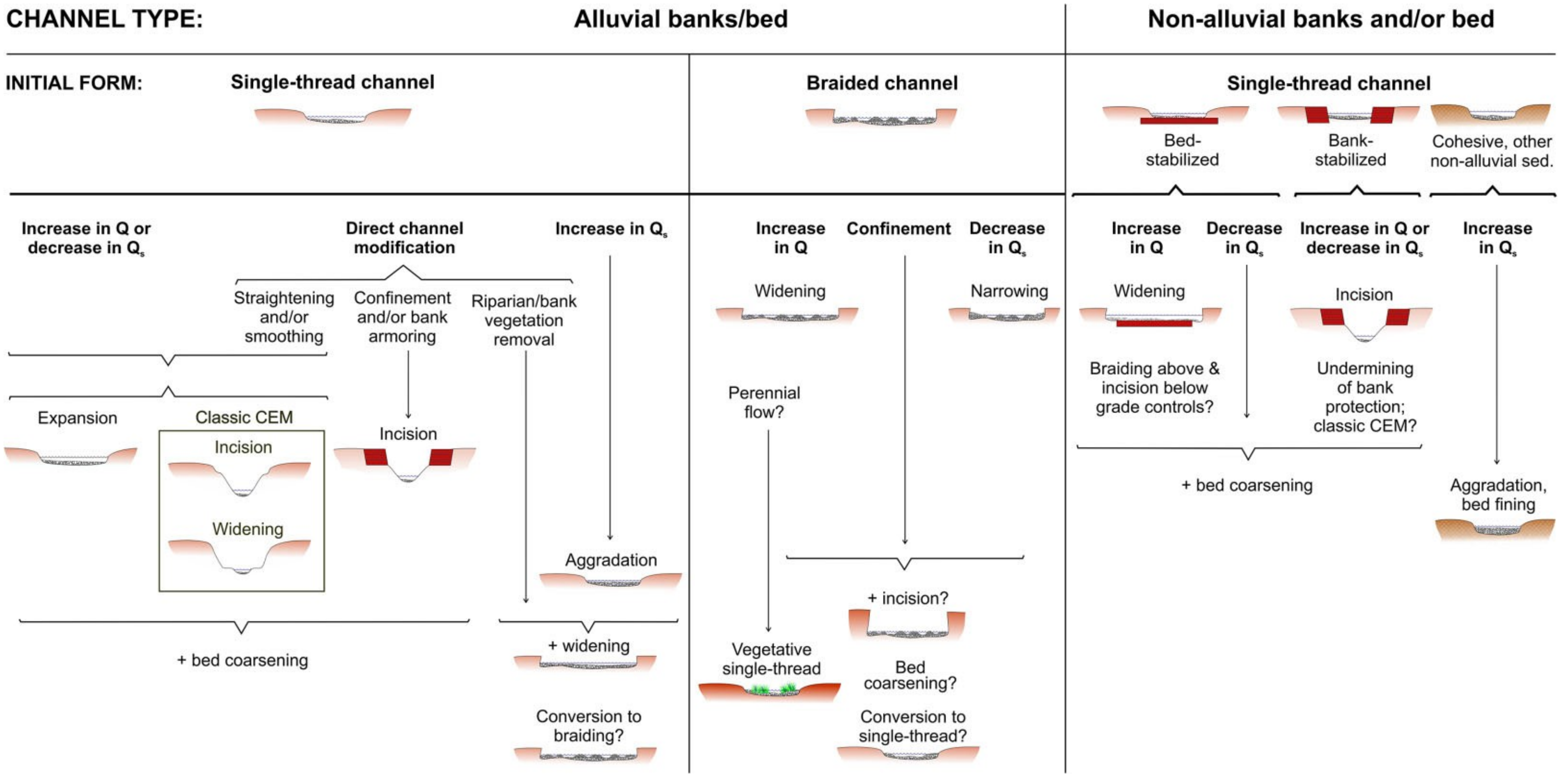

Figure 5 The urban CEM as a predictive tool, in graphical form analogous to Table 2

Notes: Read from top to bottom, with the channel type and initial form constraining the range of disturbances (e.g. increases in Q or direct channel modification) that can produce a channel response, as diagrammed below. Q = water discharge, Q_s = sediment discharge; ‘Classic’ channel evolution model as described in Figure 3

Table 3 Summary of the urban CEM as used for diagnosis of causality from observed responses. The list of observed conditions (left-hand column) spans the range of common channel and floodplain relationships, normally identified using criteria such as those in Simon (1994, his Table 20)

		Current channel type				
		Multi-thread alluvial	Single-thread alluvial		Single-thread, bed-stabilized	Single-thread, bank-stabilized
Observed condition	Incised	Increased Q or decreased Q_s	Increased Q, decreased Q_s, and/or reduced roughness (potentially ex-multi-thread?)	Stages III–IV of Simon and Hupp (1986)	N/A	Increased Q or decreased Q_s, or as response to confinement (Stages III–IV of Simon and Hupp (1986))
	Incised and bank failures	Increased Q or decreased Q_s		Stages IV–V	N/A	N/A
	Stable and floodplain-disconnected[1]	Increased Q or decreased Q_s		Stage V	N/A	Increased Q or decreased Q_s (Stage V of Simon and Hupp (1986))
	Unincised, with bank failures	Increased Q, increased Q_s, and/or riparian vegetation removal (ex-single thread?)	Increased Q_s or riparian vegetation removal		Increased Q, decreased Q_s, or riparian vegetation removal	N/A
	Stable and floodplain-connected	No impact, or increased Q (adjusted), or increased Q_s and/or bank vegetation removal (ex-single thread?)	No impacts, minor Q increase, or proportional increases in Q and Q_s		No impacts, or increased Q (adjusted)	No impacts, or proportional increases in Q and Q_s

Notes: [1] Floodplain connectivity refers to the opportunity for moderate-recurrence flood discharges to spill onto the adjacent floodplain, thus dissipating much of the erosive energy of increasing flows (Segura and Booth 2010). 'Disconnection' is a useful indicator of incision in many (but not all) regions. CEM = channel evolution model; 'Q' = discharge; 'Q_s' = sediment discharge

Figure 6 Four urban streams, expressing fundamental differences in their respective regional and watershed settings
Notes: Top left, the Avon River in Christchurch (NZ); top right, McEnnery Canyon, Acton CA (USA); lower left, Chester Creek, Duluth MN (USA); lower right, Easter Lake Creek, Federal Way WA (USA)

trajectories based on a single snapshot of channel form. Recognizing channel change using multiple indicators or successive observations over time, however, will typically improve the diagnostic or predictive utility of any evolutionary model.

Watershed differences and urban channel evolution

The evolution of a disturbed channel always occurs in a context – hydrological, physiographic, biological and geomorphic (Figure 2; Brierley 2010). Thus, diagnosing and treating the causes of degradation on any particular stream must recognize that process drivers are not all equally important everywhere, they do not all respond identically to human action, and their expression at a specific channel location is not the same everywhere (Figure 6). Some of these differences can be anticipated within a regional, spatially explicit geographical framework (e.g. Snelder and Biggs 2002; Olden *et al*. 2012); others vary within a single watershed at scale(s) only discernible through site-specific analyses (e.g. Stewart *et al*. 2001; Marzin *et al*. 2013). Recognizing these differences can improve applications of the urban CEM by focusing on those disturbances and outcomes most likely in a given urban watershed.

Regional factors

Overarching commonalities of climate-driven hydrology, sediment-delivery rates, watershed relief and channel–vegetation interactions can be identified over broad regions. A systematic evaluation of these factors at a continental or global scale is beyond the scope of the present discussion, but a few key considerations can streamline applications of the urban CEM.

In humid regions, particularly those supporting perennial streamflow with only modest increases from low- to high-frequency flood peaks (e.g. the 'stable baseflow streams' of Kennard *et al*. (2010) [Australian continent] or the 'superstable groundwater streams' of Poff (1996) [continental USA]), hydrologic and geomorphic responses to watershed urbanization will be enhanced, given the low natural variability of flood magnitudes and thus the opportunity for unprecedented, many-fold increases in flood peaks and disturbance frequencies in urban watersheds. Abundant rainfall also promotes greater vegetation growth, vegetation–channel interactions, and thus dependencies of geomorphic form on (disturbance-prone) biota. In contrast, regions with streams having frequent periods of no flow (Kennard *et al*.'s 'highly' or 'extremely intermittent' streams; Poff's 'harsh intermittent' streams) tend to be dominated by relatively infrequent but (very) large flood events, with limited influence from riparian vegetation or in-channel large woody debris; and they can experience long periods of geomorphic quiescence that may be mistaken for 'stability' or 'equilibrium' until the next large storm occurs (Hawley and Bledsoe 2011).

Channels in regions of high natural sediment loading should be most susceptible to urban-induced reductions in sediment delivery, as typified by areas of southern

California (southwestern USA) with intense storms, weak rocks and high watershed relief (Bledsoe *et al*. 2012; Booth *et al*. 2014). Conversely, channels in regions of intrinsically low watershed sediment delivery (e.g. Nelson and Booth 2002) are less likely to express geomorphic changes resulting from yet further urban-related reductions in sediment load, although the downstream deposition of eroded sediment from upstream incision can quickly overwhelm channel transport capacities and foster localized responses associated with increased sediment (Chin *et al*. 2013).

Reach- and watershed-scale factors

Within any given watershed, local differences in watershed attributes and processes (Figure 2) can influence the evolution of urban channels as (or more) strongly than regional factors. Variations in valley slope, network position, sediment delivery, floodplain extent and channel confinement can determine whether a reach is naturally single- or multi-threaded, and how susceptible it may be to a change in planform (Eaton *et al*. 2010) following urbanization. Local channel gradients and natural grade controls are primary determinants of incision susceptibility as a response to urbanization (Booth 1990), and these factors can vary greatly throughout a single channel network. The presence and importance of bank vegetation and in-channel woody debris is not uniform from headwaters to mouth of rivers, even in humid regions where these influences are widespread (Gurnell *et al*. 2002), and so the consequences of urban removal of riparian and in-channel vegetation can differ widely not only between regions but also along an individual channel. This is not a comprehensive list of the watershed-scale factors that can influence the trajectory of an urban channel, but it should provide some guidance for more specific, nuanced applications of the urban CEM as part of a systematic approach to sustainable urban stream restoration (Shoredits and Clayton 2013).

Summary

A CEM, specifically focused on the disturbances characteristic of urban watersheds, can provide an organizing framework for interpreting the observed condition of urban streams and predicting the trajectory of future morphologic changes. Both are critical steps for implementing effective and self-sustaining stream restoration measures. Restricting the range of possible disturbances and channel forms only to just those common in urban watersheds renders tractable what would otherwise be an impossible effort to characterize all streams in all settings, a limitation of all CEMs whether explicitly acknowledged or not.

Systematic differences in the evolutionary trajectory of urban streams can be recognized at both regional and within-watershed scales, but only a few of those differences are sufficiently pervasive and influential to modify the dominant and near-universal impacts of urbanization on streams, particularly increases in discharge and direct modification of the channel bed and banks. Future efforts to identify coherent geographic regions with similar hydrologic, physiographic and ecological influences should refine the application of the urban CEM and improve its predictions of channel evolution in any given setting. However, urbanization is such an overwhelming disturbance that many local and regional differences are nearly irrelevant to the response of channels facing dramatic increases in flows and the hardening of channel boundaries.

Even without a fully developed, multi-scale framework, employing a structured approach should yield greater success in identify underlying causes of urban stream degradation, selecting feasible and regionally appropriate restoration targets, and implementing specific restoration techniques that effectively address those causes given the guidance provided by the prior experience of others. ‘Success’ can then be measured by the degree to which regionally appropriate reference conditions have been recovered, and whether the channel form and function can persist in the environment without further human intervention. However, comprehensive restoration planning requires independent evaluation of all of the features of a stream system (Figure 1) that may be disturbed in an urban setting. Channel form alone, no matter how stable or well-adjusted it may be, cannot fully replace a more comprehensive understanding of watershed health.

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