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Restoring geomorphic integrity in urban streams via mechanistically-based storm water management: minimizing excess sediment transport capacity

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Abstract

Stream channel erosion, enlargement, and habitat degradation are ubiquitous in urban watersheds with conventional stormwater management that increase channel-eroding flows relative to undeveloped watersheds. Hydrologic-based restoration aims to discharge a more natural flow regime via stormwater management interventions. Whether such interventions facilitate geomorphic recovery depends, in part, on the degree to which they restrict discharges that would otherwise contribute to channel erosion. Erosion potential (E), the ratio of post-developed to predeveloped sediment transport capacity, provides a simplified, mechanistic framework to quantify the relative influence of stormwater interventions on the geomorphic effectiveness of the flow regime. This paper compiles ca. five years of data following stormwater-based interventions in three distinct settings in the United States and Australia to demonstrate how the E framework can elucidate the role of hydrologic restoration interventions in facilitating trajectories of geomorphic recovery (or lack thereof). In a previously developed watershed with unstable streams, substantial reductions in E in one stream coincided with a trajectory of geomorphic recovery, whereas the control stream without E-reducing interventions exhibited continued instability. Furthermore, a stream downstream of a greenfield development that optimized their stormwater control measures to match the sediment transport capacity of the predeveloped regime (E = 1) was able to maintain a recovery trajectory in a legacy-impacted setting that is otherwise highly susceptible to hydromodification. Streambed material size, channel evolution stage, and the hydrogeomorphic setting also likely affect the level of E reduction necessary to promote geomorphic recovery, with coarser-grained and over-widened streams potentially needing less reduction than finer-grained and more entrenched channels. Although available space and funding will limit the ability to fully reduce E in previously developed watersheds, these case studies underscore the value of using stormwater control measures to maximize reductions in E if geomorphic stability is a goal of stormwater interventions.

Keywords Urbanization · Detention basin retrofits · Stormwater management · Transport capacity · Stream recovery, stream restoration

Introduction

Streams draining urban landscapes with conventional stormwater management tend to be systematically degraded (Paul and Meyer 2001; Walsh et al. 2005; Booth et al. 2016). Increased runoff and more efficient drainage networks in urban settings amplify the erosive power of the flow regime leading to channel incision (Harvey et al. 1983; Booth 1990), enlargement (Hammer 1972; Hollis and Luckett 1976; Galster et al. 2008; Chin et al. 2017; Bevan et al. 2018; Sullivan et al. 2020) and cycles of geomorphic instability (Booth and Fischenich 2015). As a result, urban streams can have less stable substrate (Pizzuto et al. 2000; Booth and Henshaw 2001) and simplified/impaired habitat (Vietz

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et al. 2014; White and Walsh 2020) with gravels/cobbles embedded by fine sediment (Zeiger and Hubbart 2019) that is often attributable in part to intensified rates of bed and bank erosion (Trimble 1997; Chin 2006; Wilson et al. 2007; Simon and Klimetz 2008). Trajectories of channel instability such as the "classic" Channel Evolution Model (CEM) of Schumm et al. (1984, Fig. 1) can lead to entrenchment that can further amplify the erosive power of the flow regime resulting in additional channel erosion and streambed disturbance (Watson et al. 2002; Anim et al. 2019). Even in the absence of chemical pollution and habitat degradation, increased frequencies of streambed disturbance can drive significant decreases in macroinvertebrate richness and biotic integrity, underscoring the biological relevance of the natural bed disturbance regime (Poff 1992; Holomuzki and Biggs 2000; Hawley et al. 2016; Jordt and Taylor 2021).

One aim of hydrological restoration projects in urban watersheds is to mitigate chronic channel erosion by facilitating geomorphic recovery in the receiving stream network (e.g. Stein et al. 2012). We define geomorphic recovery as a return to geomorphic equilibrium (i.e. Stage 5 in Fig. 1 for single-thread channels) including relatively stable channel banks, a sediment transport regime that maintains sediment continuity (neither excess scour nor aggradation), and a channel form that maintains its overall size and shape over time (no notable enlargement or contraction) (Biedenharn et al. 1997). By this definition, geomorphic equilibrium can exist across a variety of channel forms including braided channels and novel stream systems that are far removed from natural conditions. Geomorphic equilibrium underpins and interacts with a range of ecological and societal values of streams (Somerville and Pruitt 2004; Polvi et al. 2020), including water quality (e.g. suspended sediment caused by channel erosion), elements of in-stream ecology (e.g. substrate quality and disturbance regime; habitat complexity), vegetation (e.g. loss of trees due to bank erosion; burial or scour of aquatic and riparian vegetation), infrastructure failure and public safety (e.g. damage to bridges, roads, or buildings due to bank erosion), recreation (e.g. swimming; fishing) and aesthetic concerns.

Channel form is influenced by any discharge that has the capacity to mobilize the bed or bank material (Wolman and Miller 1960). For example, when streambed particles are transported downstream during an event but not replaced by particles delivered from upstream reaches, the stream becomes incrementally deeper, and banks become steeper and more prone to failure (Simon 1989; Simon and Rinaldi 2000, 2006). The potential geomorphic influence of any given hydrologic event can be quantified by its sediment transport capacity (Biedenharn et al. 2001), which is calculated as the integration of the sediment transport rate (t/hr) for each instantaneous discharge multiplied by the cumulative duration that each discharge occurs (hr) over the hydrograph(s). All else being equal, an event with the capacity to transport 100 t of bed sediment has more potential to enlarge channels and disturb substrates than an event with a capacity of 10 t. Given the potentially complex consequences of geomorphic channel degradation, restoring predeveloped sediment transport capacity could be considered a keystone objective in hydrologic restoration projects aimed at facilitating geomorphic stability.

Urban streams typically have much higher sediment transport capacity than their predeveloped condition (MacRae 1991, 1993; Booth and Jackson 1997; Papangelakis et al. 2019). They also tend to have altered sediment supplies relative to their predeveloped conditions (Wolman 1967; Russell et al. 2017). Both unmanaged and conventionally managed (e.g. flood control basins) stormwater runoff typically create more events that exceed the critical discharge ($Q_{critical}$) for incipient motion of the bed material (Booth and Jackson 1997; Bledsoe 2002), as well as longer durations of bed-mobilizing flows (Hawley and Bledsoe 2011; Rosburg et al. 2017). Sediment tracer studies in urban streams have verified that the increased power to transport streambed sediment coincides with increased rates of coarse sediment transport (Papangelakis et al. 2019; Cain et al. 2020).

The ratio of the sediment transport capacity between the urban flow regime and the predeveloped flow regime is referred to as the erosion potential (E, Eq. 1) (MacRae 1993; Bledsoe 2002), or load ratio (Hawley and Bledsoe 2013),

$$E = \frac{L_{developed}}{L_{predeveloped}} \quad (1)$$

where E = erosion potential (dimensionless), $L_{developed}$ = sediment transport capacity of a management scenario (t or m^3), and $L_{predeveloped}$ = sediment transport capacity of the predeveloped regime (t or m^3) using the same sediment transport equation (e.g. Einstein 1942; Meyer-Peter and Müller 1948; Wilcock and Crowe 2003). An erosion potential greater than one indicates an excess of sediment transport capacity over pre-developed conditions, often the primary driver for the cycles of channel incision, widening, and enlargement that is typical in many urban stream settings (Papangelakis et al. 2019; Russell et al. 2020). Hawley and Bledsoe (2013) found that erosion potential had more predictive power for stream stability than empirical models that relied on other surrogates for urban stream power such as impervious area. If a channel formerly in equilibrium undergoes an increase in sediment transport capacity it can use that extra power to remove larger amounts of bed and bank material than would have occurred under the predeveloped regime. The greater the relative departure from the predeveloped regime, the more potential for channel instability and enlargement. Managing stormwater to minimize departure from the predeveloped sediment transport capacity is therefore a

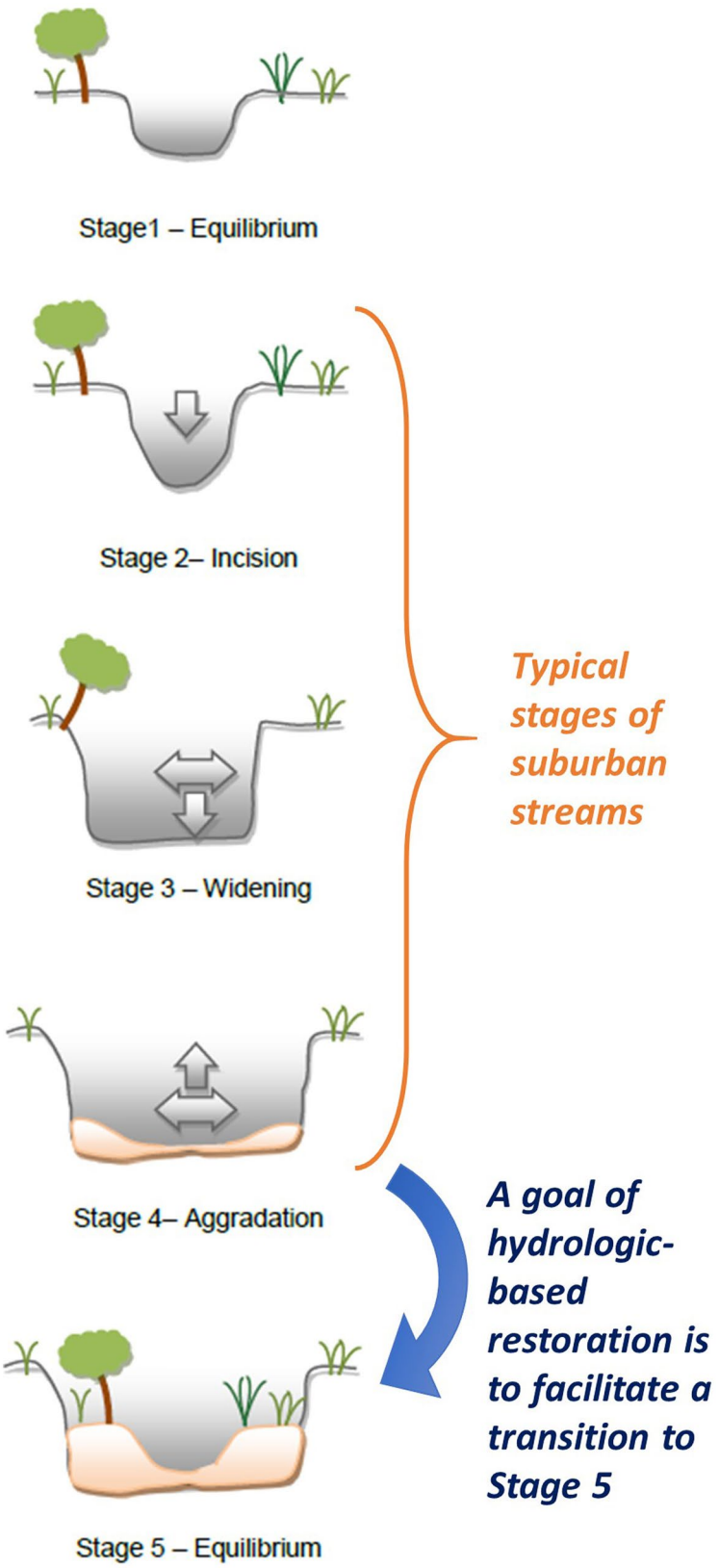


Fig. 1 Channel Evolution Model (CEM) adapted from Schumm et al. (1984) and Hawley et al. (2012). The goal of hydrologic-based geomorphic restoration is to facilitate a return to equilibrium (Stage 5 in this CEM)

mechanistically-relevant approach to protect or restore geomorphic stability and related societal values of streams.

We suggest that E can be used as a mechanistically-based management framework for stormwater control measure (SCM) design and watershed-scale hydrologic restoration aimed at restoring geomorphic stability in previously developed watersheds, as well as protecting geomorphic integrity in previously undeveloped watersheds. Given that opportunities for intercepting and attenuating stormwater in previously developed watersheds can be both rare and expensive, this paper highlights the value in optimizing retrofits to minimize E and match the predeveloped sediment transport regime to the extent feasible. In this paper we present a framework for the application of E as a management tool for guiding appropriate stormwater interventions (Fig. 2), and apply the E framework to three watersheds in North

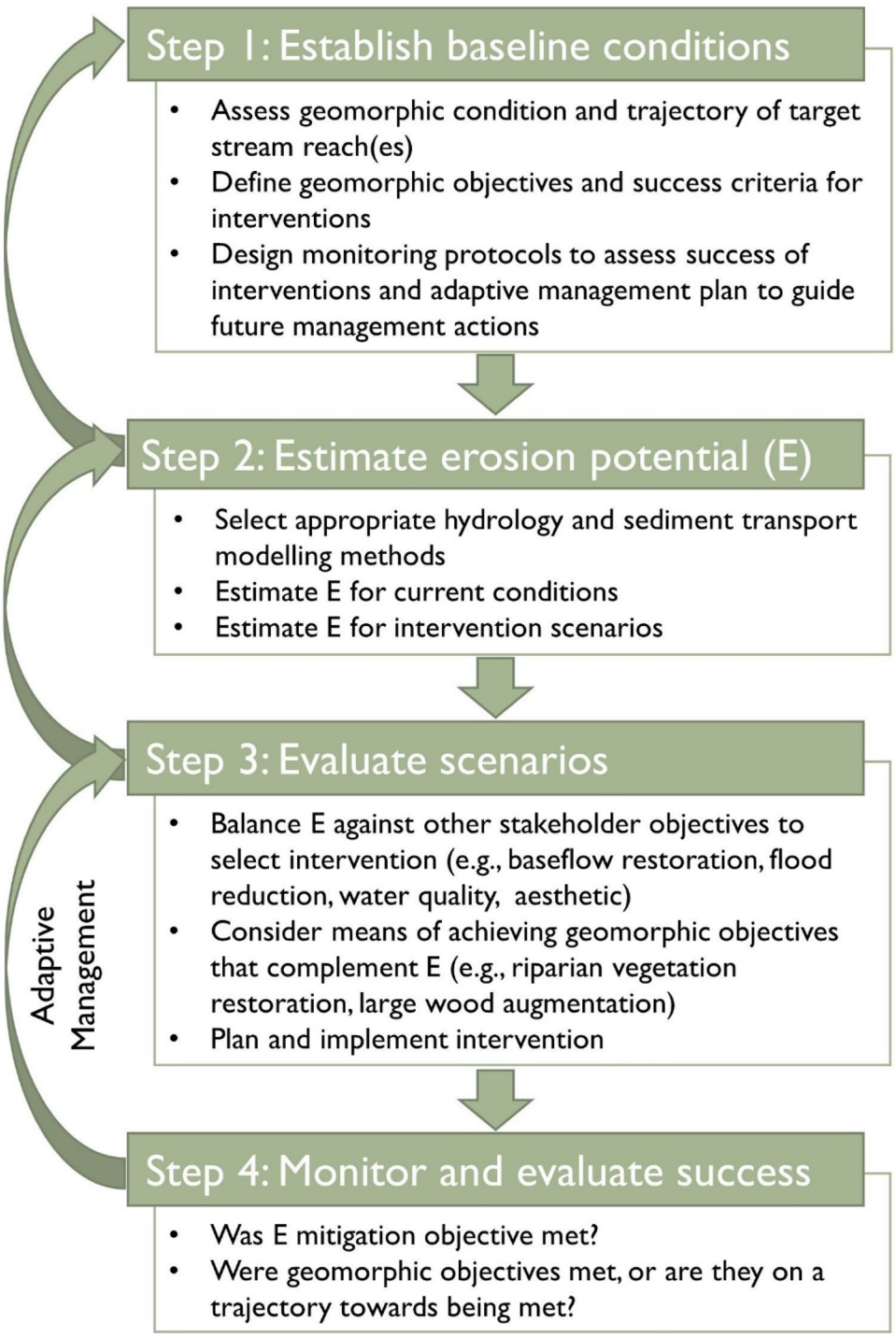


Fig. 2 Erosion potential (E) framework

America and Australia. The paper concludes with a discussion of insights from the case study applications as well as recommendations regarding applications to other settings.

Erosion potential (E) as a management framework

The E framework includes four steps, which are described in detail in the following sections: (1) establish baseline conditions, (2) estimate E, (3) evaluate scenarios, and (4) monitor and evaluate success.

Step 1: establish baseline conditions

Baseline watershed and geomorphic conditions of the receiving stream should be established prior to developing E-based interventions. For example, is the watershed entirely undeveloped and slated for a new "greenfield" development where pervious soil and vegetative cover will be replaced by impervious pavement and structures, or is the watershed already developed and being considered as a candidate for SCM retrofits? Does the receiving stream have an existing flow gage or previously developed model that can be used for hydrologic analysis or will a rainfall-runoff model need to be developed for the watershed?

To establish baseline geomorphic conditions, a rapid, reach-scale assessment can establish the current stage(s) of channel evolution (e.g., Schumm et al. 1984) and the trajectory of future change in the absence of successful stormwater interventions. For example, many urban streams undergo incision-based trajectories that can adversely impact bed and bank stability for decades (e.g., Booth 1990; Hawley et al. 2020). Other streams may be recovering from legacy impacts with signs that they are nearing a return to geomorphic equilibrium. Channel hardpoints (e.g., exposed bedrock, artificial culverts, etc.) can be common in urban streams and can provide spatial disruptions to incision-based trajectories (e.g., Hawley et al. 2013; Taniguchi et al. 2018). The geomorphic valley type (e.g., confined vs. unconfined) and valley transitions (e.g., steep confined to flat unconfined) can also constrain or exacerbate channel responses to watershed urbanization. A rapid assessment can not only support theclassification of CEM stage but also establish a representative site(s) for geomorphic data collection that will inform the subsequent modeling steps. This includes a standard pebble count (Bunte and Abt 2001) and channel cross section at a representative riffle in addition to a longitudinal profile (Harrelson et al. 1994) in support of the hydraulic and sediment transport modeling (Hawley and Vietz 2016) discussed in Step 2.

Step 2: estimate erosion potential (E)

To calculate E (Eq. 1), estimates of sediment transport capacity are required for both the pre-development and post-development scenarios. For a greenfield development, the goal may simply be to maintain an E of 1 such that the post-developed sediment transport capacity matches the pre-developed sediment transport capacity. In previously developed watersheds that are candidates for SCM retrofits, additional scenarios may be needed to compare how the E of the proposed retrofit condition ($E_{post\text{-}retrofit}$) compares to the current conditions ($E_{pre\text{-}retrofit}$, see Step 3 for additional guidance on scenario evaluation). All such estimates of E require 1) a sediment transport relationship to relate flow to instantaneous sediment transport and 2) a method to estimate and accumulate flow over the selected analysis period.

There are many methods for computing sediment transport, and the E framework can use any equation as long as it is consistent among comparison groups. Over a century of river mechanics research has resulted in numerous sediment transport methods (Gomez 1991), but they all tend to converge on the idea that higher stream power, shear stress or velocity produces greater geomorphic responses in streams. Even relatively simple thresholds of unit stream power have been correlated to risks of sizable channel widening during large floods (Yochum et al. 2017). In the absence of highly calibrated models, calculations of transport capacity ratios may provide greater utility, especially where absolute accuracy is less important (Russell et al. 2020). For example, a ratio approach using the Meyer-Peter and Müller (1948) equation with adapted parameters from Wong and Parker (2006) was used in southern California (Hawley and Bledsoe 2013) and Northern Kentucky (Hawley et al. 2017) in the United States (U.S.), whereas a ratio approach using the two-fraction model of Wilcock and Kenworthy (2002) was used in streams in Victoria, Australia (Russell et al. 2020). One of the factors underpinning the success of the E framework is that the sediment transport computations used to calculate E (Eq. 1) for different scenarios in a given stream must be based on the same sediment transport method. Although users can tailor their application of E to the sediment transport equation most appropriate for their setting, it is imperative that the sediment transport capacity for the developed and undeveloped scenarios use the same sediment transport equation.

Similarly, there are numerous methods for developing the hydrologic inputs that are necessary for the E framework, and they too should be consistent across comparison groups and aligned with the study goals and design. For example, if using the E framework to optimize SCM designs, one might use a range of standard design storms that are commonly used in the management community (e.g. 2-yr, 10-yr, 100-yr). Alternatively, one could use continuous simulation

to model a representative precipitation record that is commensurate with the expected frequency of bed entrainment for the given stream (e.g. a few decades for a gravel/cobble stream, a century or longer for boulder streams (Hawley and Vietz 2016)). Whether using design storms or continuous simulations, the same precipitation record/design storms should be used to model all of the evaluation scenarios (e.g. predeveloped, management scenario 1, scenario 2, etc.). In instances where gage records of the pre-intervention and post-intervention periods are available, E can be calculated directly from the observed flows. In this application of the E framework, it is less about evaluating the merits of competing stormwater interventions at the design/planning phase and more about illuminating why the implemented stormwater management interventions facilitated (or failed to produce) the expected geomorphic response. For example, E can help untangle the role of climate by synthesizing multiple years of hydrologic records into a single number. In this way, the E framework builds on the long history of using river mechanics computations to reduce complex phenomena to a representative value (e.g., effective discharge, Q_{eff} (Wolman and Miller 1960; Biedenharn et al. 2001) or the discharge associated with 50% of the cumulative sediment transport over the flow record, Q_{s50} (Bledsoe et al. 2016; Stroth et al. 2017)).

Step 3: evaluate scenarios

The E framework presents the opportunity to evaluate numerous competing design scenarios similar to the "value engineering" step that is commonly performed by design professionals. For example, on a greenfield site with a goal of E = 1, the SCM(s) can be optimized by changing its characteristics (e.g. greater storage, smaller secondary orifice, etc.) until arriving at a post-development scenario that matches the sediment transport capacity of the predeveloped regime. Similarly, for previously developed watersheds being evaluated for retrofit opportunities, numerous SCM scenarios can be evaluated through the E framework until arriving at a solution that maximizes the reduction in E (i.e. maximizes $E_{post\text{-}retrofit} - E_{pre\text{-}retrofit}$) within the context of other project objectives. Given that urban waterway management requires balancing a set of complex and sometimes competing priorities, e.g. ecological integrity, stability, flood protection, water quality and aesthetics, it is imperative to evaluate E alongside other objectives for sustainable urban stream management. This is especially true given that it is usually impractical to perfectly mimic the pre-development hydrograph for all parts of the flow regime. For example, Alternative A (E = 1.36) in Fig. 3 better matches the shape of the predeveloped hydrograph, but Alternative B (E = 1.12) comes closer to matching the sediment transport capacity. Depending on other stakeholder values (e.g. baseflow restoration, flood stage reduction, etc.), along with how each design performs across a synthesis of design storms (or continuous simulations), a manager can make an informed decision on which intervention (or combination thereof) to invest in.

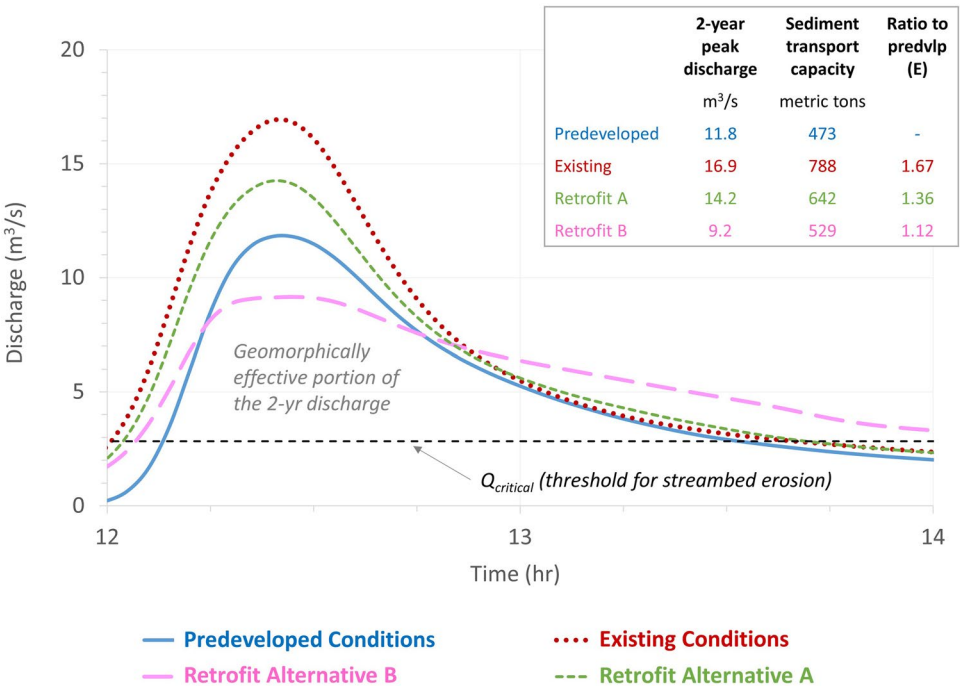


Fig. 3 Alternatives analysis from a northern Kentucky watershed comparing the influence of retrofit alternatives on the hydrographs and sediment transport capacity for the 2-year discharge. Alternatives that minimize the departure from predeveloped (reference) conditions for all disturbance-inducing events have a better chance at facilitating geomorphic recovery than alternatives that do not appreciably reduce E

Step 4: monitor and evaluate success

Monitoring and evaluation are critical to understanding whether an intervention is successful and if additional or alternative interventions are needed to achieve geomorphic objectives. Monitoring can include the success of the intervention in reducing transport capacity (e.g. flow gaging or monitoring function/operation of intervention structures), as well as its success in fostering geomorphic stabilization or recovery (e.g. repeat geomorphic surveys and assessments). It is important to note that the baseline assessment (Step 1) should inform the success criteria of the future SCM interventions. For example, success in a developed watershed in a stream undergoing an incision-based trajectory may be to induce a transition to an aggradational trajectory, whereas success in an equilibrium (or near equilibrium) stream downstream of a greenfield development may be to simply maintain geomorphic equilibrium. What success looks like for a particular intervention will also be heavily dependent on geomorphic and social context, taking into account the stream's potential for recovery along with the ecological and social values that could be supported by a geomorphically stable stream. The baseline assessment should also inform the downstream zone of influence from the SCM that the monitoring should encompass, how many locations within the reach(es) are needed to adequately detect channel evolution or lack thereof, and over what time period changes are likely to be detectable. Monitoring reference or control sites (e.g. upstream of intervention or in nearby catchments) is typically critical to distinguish the effects of the intervention from background effects (e.g. due to climate variability). Where geomorphic objectives are not met, geomorphic trajectory can be assessed to predict whether they might be met over time, or if further intervention is required. In this way, adaptive management processes can be implemented to iterate design, implementation, monitoring and evaluation under the E framework.

Case studies

We applied the E framework in three watersheds (Table 1) with stormwater interventions in hydro-geomorphically distinct regions: southern California USA, northern Kentucky USA, and Victoria Australia (Hawley and Vietz 2016). Each watershed had SCMs applied with the aim of protecting or restoring geomorphic or ecological condition. This study provides the opportunity to synthesize the effects of stormwater control on transport capacity and geomorphic recovery in three distinct contexts. The case studies employ a gradient of E applications that coincide with how practitioners, managers, and researchers are actively applying the E framework in various regions (e.g. design storm analyses vs. continuous or pseudo-continuous simulations vs. gaged flows).

It is important to note that the three case studies included in this analysis are a part of much larger independent studies/datasets that help to discern signal from noise. The California study capitalized on a large inventory of consultant-collected data, including repeat geomorphic surveys at four monumented cross sections (two upstream and two downstream of the development), but was limited by access restrictions that precluded the ability to conduct an independent field assessment. The Kentucky dataset includes repeat surveys at 61 sites over ~ 10 years that include control/reference sites where CEM stage was assessed by the same personnel using field indicators and affirmed by repeated time-series cross sections, profiles, and pebble counts (Hawley et al. 2020). Geometric surveys included repeat surveys at monumented cross sections according to industry standard methods (Harrelson et al. 1994) and bed material pebble counts after Bunte and Abt (2001). The Victoria dataset included numerous cross-sections, which together indicated geomorphic trajectory, and also included multiple control and reference sites that characterize background conditions in the absence of urbanization and mitigation.

Step 1: establish baseline conditions

The California case study is from a greenfield development where SCMs were designed to match the predeveloped sediment transport capacity (E = 1), which has been a requirement in many regions of California since ~ 2010 (e.g., County of Orange 2011). The case study included herein is from a development in southern Orange County, California draining to a stream in a historically ranched but primarily open-space watershed with a drainage area of 14.4 km^2 and 5% Total Impervious Area (TIA) post-development (Table 1). This case study leverages hydrologic modeling results and repeat channel cross sectional survey data and photos collected by private consultants as a part of the development's permits (PACE 2019). Stream channel cross sectional surveys of the study tributary, Chiquita Creek, occurred pre- and post-development at four monitoring locations – two downstream and two upstream of the development. The sites downstream of the development were located at two geomorphically–distinct locations: a less defined, wide channel in the immediate receiving stream ("CA 1") and a more defined split channel separated by a wide central bar located 450 m downstream ("CA 2"). Both upstream sites were located at v-shaped entrenched channels that were upstream of "CA 1" by 1.8 km and 3 km. Both CA 1 and CA 2 were downstream of an orchard and received irrigation runoff that resulted in a highly vegetated channel prior to the suburban development. Prior to development, CA 1 and CA 2 were in an aggradational trajectory (CEM Stage

Table 1 – Case study locations, characteristics, and methods. TIA = total impervious area

Case study	California	Kentucky	Victoria
Stream	Cañada Chiquita Creek	Unnamed tributary to Woolper Creek	Little Stringybark Creek
Lat/Long	33.5421, -117.6114	39.0496, -84.713	-37.7734, 145.4111
Drainage area (km^2)	14.4	1.3	4.3
TIA (%)	5	12	14
Climate type[a]	BSk (cold semi-arid)	Cfa (humid temperate)	Cfb (temperate oceanic)
Mean annual rainfall (mm)	407	1080	997
Catchment relief (m)	286	25	131
Geology	Sandstone and mudstone	Limestone and shale	Rhyolite and rhyodacite
Bed sediment class	Sand	Cobble	Sand
Catchment land cover	Historically ranched, undeveloped: mixed shrub, grassland, orchard, urban, and open space development	Historically pasture/forest, with recent industrial development	Peri-urban: mixed suburban, rural residential, forest and agricultural
Nature of intervention	Hydromodification detention basin for greenfield development	Retrofitted detention basin outlet	Retrofitted distributed measures (e.g. rainwater tanks, rain gardens)
Number of sites (including study, control, and reference)	4	3	3
Number of years evaluated following SCM interventions	4	6	5
Transport capacity equation	van Rijn (1984a, b) with modifications by Spasojevic and Holly (1994)	Meyer-Peter and Müller (1948) with Wong and Parker (2006) corrections	Wilcock and Kenworthy (2002)
Flow integration method	Range of design events integrated over a flow-frequency curve	Largest 22 events over 40-year period	Continuous stream gage data (10-year record)
Comparison method	Modelled flow scenarios	Modelled flow scenarios	Before-after control-reference-intervention (BACRI) gaged flows
Reference	(Phillips et al. 2013)	(Hawley et al. 2017)	(Russell et al. 2020)

[a](Peel et al. 2007)

4). In contrast, the entrenched upstream control sites were assessed to be in a degradational trajectory (CEM Stage 2), which was likely attributable in part to historic cattle grazing and ranch operations over the last 60 years.

The Kentucky case study is from a previously developed basin where the original SCM was retrofit to release a less erosive flow regime, which is described in detail by Hawley et al. (2017). In December 2013, a passive retrofit device was installed on a conventional flood control detention basin that drains ~ 0.09 km^2 with 50% TIA. The objective of the retrofit was to restrict stormwater discharges during most precipitation events, including the 3-month, 6-month, and 1-year design storms, to less than the $Q_{critical}$ for the receiving stream and reduce E to the fullest extent possible while still containing the 100-yr storm within the detention basin. Hydrologic modeling of standard design storms documented that the 3-month, 6-month, and 1-year events were all events that exceeded $Q_{critical}$ under the pre-retrofit conditions. Three in-stream monitoring sites were established in the receiving stream network ca. one year ahead of the retrofit installation: the immediate receiving stream of the SCM ("Spur", DA = 0.17 km^2, 45% TIA), an upstream control site on a separate tributary that did not receiving discharge from the SCM ("US Site", DA = 1.1km^2, 7.8% TIA), and a downstream site ("DS Site", DA = 1.31 km^2, 12.4% TIA) that received discharges from both the Spur and the US Site. Before the retrofit, both the Spur and the DS Site were assessed to be on a degradational trajectory with notable bank erosion (CEM Stage 3), whereas the US Site was assessed to be in a state of relative equilibrium with vegetated benches (CEM Stage 1). See Hawley (2021) for a detailed inventory of the observations at each site.

The Victoria case study is from a previously developed watershed where distributed SCMs were retroactively installed with a goal of discharging a more natural flow regime. The peri-urban watershed drains 4.3 km^2 with 14% TIA, including 9% Effective Impervious Area (EIA) prior to retrofitting. The site is part of a watershed-scale before-after control-reference-intervention (BACRI) experiment (Walsh et al. 2015, 2021) with three reference sites and two control

(suburban, without intervention) sites, all with continuous streamflow gaging. The case study analysis used 3 sites: the intervention site, the most comparable reference site as a surrogate for pre-development conditions for computation of E and the most comparable control site to compute E for a developed, unmitigated scenario. The primary purpose of the intervention was to restore in-stream ecological conditions by mimicking the flow regime (runoff frequency, baseflows, contaminant concentrations and total runoff volume) of nearby forested catchments. No erosion potential objective was defined but the intervention is expected to reduce E as a byproduct of reducing runoff magnitude and frequency. While geomorphic monitoring was not originally part of the study design, pre-intervention geomorphic assessment for a related project in 2011 provided an opportunity to repeat the assessment post-intervention. Pre-intervention, the site was on a trajectory of channel degradation and bank erosion (CEM Stage 2 or early Stage 3). We can thus assess the geomorphic effect of an intervention that was not specifically designed using the erosion potential framework.

Step 2: estimate erosion potential (E)

The approaches used for transport capacity computations, integration over the flow regime and scenario comparisons for the case study sites, are summarized in Table 1. It is anticipated that the scale of differences in E values in this comparative study (see Table 2) overwhelms any slight variations in E that could be attributable to differences from the regionally preferred methods described below.

For southern California, sediment transport capacity was modeled for a range of design events (2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storm events) under pre-development and post-development (mitigated) scenarios using the US Army Corp of Engineer's SAM. AID subroutine and reach-specific cross-sectional geometry and sediment data (Phillips et al. 2013). To evaluate the long-term sediment transport capacity across a range of flow conditions, a frequency curve for sediment transport capacity was estimated from the transport capacity for each design event of known probability of occurrence following the procedures outlined by the Arizona Department of Water Resources (1985). The approximate (trapezoidal) area under the frequency curve represented the estimated long-term mean annual sediment transport capacity (L_m) and was calculated using the following equation:

$$\begin{aligned} L_m = {} & 0.01(L_s)_{100} \\ & + 0.01\frac{(L_s)_{100} + (L_s)_{50}}{2} \\ & + 0.02\frac{(L_s)_{50} + (L_s)_{25}}{2} \\ & + 0.06\frac{(L_s)_{25} + (L_s)_{10}}{2} \\ & + 0.1\frac{(L_s)_{10} + (L_s)_5}{2} \\ & + 0.3\frac{(L_s)_5 + (L_s)_2}{2} \\ & + 0.5\frac{(L_s)_2}{2} \end{aligned} \quad (2)$$

where L_s is the sediment transport capacity for a given flood event that is multiplied by the probability of occurrence of that flood in one year. E was calculated as the average annual sediment transport capacity in the receiving stream of the post-development (mitigated) watershed divided by that of the pre-development watershed. On this greenfield

Table 2 – Case study sediment sizes, sediment transport ratios, and qualitative assessment of geomorphic recovery

	Bed Sediment Class	d_{50} (mm)	Erosion Potential (E)			Induced/Maintained Trajectory of Geomorphic Recovery?
			Pre-intervention	Post-intervention	%Change	
Southern CA New Development[a]	Sand	< 2	1.0	1.0	-	Yes
Kentucky Retrofit[b]	Cobble	74	18.2	10.7	-42%	Yes
Victoria Retrofit[c]	Sand	< 2	8.6	9.7	13%	No

[a]Based on SCM design and sediment transport modeling at a vegetated channel as selected by an outside consultant. "Pre-intervention" and "post-intervention" use the same standard design storms for pre-development and post-development conditions (with SCMs). See Phillips et al. (2013) for more detail

[b]Pre-intervention" and "post-intervention" use the same real events (the top 22 events over a 40-year record) to compare pre-retrofit and post-retrofit sediment transport capacity as standardized by the undeveloped sediment transport capacity for the same storms. See Hawley et al. (2017) for more detail

[c]The "pre-intervention" period in the Victoria case study captures the 5-year retrofit installation phase (2010–2014) whereas the "post-intervention" period (2015–2019) includes nominal changes in retrofit installations. E was calculated as the cumulative sediment transport of the retrofit watershed divided by that of the reference watershed, standardized on a tons/km^2 basis. See Russell et al. (2020) for more detail

development, the SCMs were intentionally designed to match the sediment transport capacity of the pre-developed regime, resulting in an E = 1.

In the Kentucky case study, sediment transport capacity was modeled using the top 22 events over a 40-year record of rainfall after previously published work by Hawley et al. (2017). "Pre-intervention" and "post-intervention" scenarios model the same real events to compare pre-retrofit and post-retrofit sediment transport capacity as standardized by the undeveloped sediment transport capacity for the same events, facilitating a comparison of E between the pre-retrofit and post-retrofit conditions. Similar to the California case study, the "undeveloped" scenario models runoff in a watershed with natural ground cover (forest/grasses) without impervious area or other stormwater conveyance interventions; however, it does not attempt to project a pre-European settlement condition (e.g. no inline beaver dams, wetland meadows, etc.). E was estimated to be 18.2 for developed (12% TIA) conditions and 10.7 for mitigated conditions. The retrofit device installed on the conventional detention basin reduced the erosion potential of the immediate receiving stream by 42% compared to pre-retrofit conditions (Table 2).

For the Victoria case study, gage data were used to model sediment transport capacity at the retrofit site, as well as one control site and one reference site, following the method of Russell et al. (2020) with an extended flow record. Gage records were divided into "during retrofit" (2010–2014) and "post-retrofit" (2015–2019) periods. The "during retrofit" period captures the intensive installation phase whereas the "post-retrofit" period (2015–2019) includes only nominal additional retrofit installations. E was calculated as the cumulative sediment transport of the retrofit watershed divided by that of the reference watershed, standardized on a t/km^2 basis. E for the control watershed was also calculated to indicate the effect of climate variation between the two periods. E in the retrofit watershed increased by 13% between the two periods, from 8.6 to 9.7; however, E increased by 68% in the control watershed (from 57 to 95) over the same time underscoring the influence of climate.

Step 3: evaluate scenarios

For the California case study, the consultant was required to optimized their SCM design until obtaining an E = 1, as required by the South Orange County Hydromodification Management plan (SOC HMP) in Orange County (2011). Their SCM was designed to meet both water quality performance criteria via infiltration and channel protection (i.e. "hydromodification") performance criteria via an E = 1 for a range of discharges from 10% of the two-year discharge (Q_2) up to the 10-year discharge (Q_{10}). Compared to the Kentucky and Victoria case studies, the California case study from the greenfield development was the only case study which achieved an E = 1 by fully matching the post-developed sediment transport capacity to that of the undeveloped regime.

For the Kentucky case study, a passive retrofit device was designed for a conventional flood control basin to restrict stormwater discharges during most precipitation events, including the 3-month, 6-month, and 1-year design storms, to less than the $Q_{critical}$ for the receiving stream. These were all events that exceeded $Q_{critical}$ under the pre-retrofit conditions. The selected design reduced the freeboard to the engineered spillway for the 100-yr design event by 21 cm but maintained the same level of service as the pre-retrofit condition by keeping the 100-yr event from overtopping the spillway. Other strategies such as excavating a larger basin or adding real-time control would have been able to reduce E even more than the selected retrofit design; however, they would have coincided with a ~ tenfold increase in retrofit cost. Given the ubiquitous nature of conventional detention basins, one of the many goals of this project was to evaluate the benefits of a low-cost (passive) retrofit with the aim of potentially being able to install many more passive retrofits that achieve meaningful (but not perfect) reductions in E with the same budget of retrofitting a single basin that achieves an E = 1.

The Victoria case study was not explicitly designed with geomorphic or sediment transport objectives, but the interventions were assessed after design and installation for their potential to reduce E. Retrofitted SCMs (e.g. leaky rainwater tanks, rain gardens) were installed on a range of properties and streetscapes, mainly between 2010 and 2014 (Walsh et al. 2015). The measures treated around half of the pre-developed effective impervious area and resulted in a reduction of EIA from 9% pre-retrofit to 6% post-retrofit. The post-retrofit EIA was estimated using the Environmental Benefit metric (Walsh et al. 2015, 2021) which accounts for imperfect SCM performance in disconnecting impervious surfaces. The watershed-scale retrofit effort was more aimed at retrofitting as much EIA as possible based on property owner participation and site-level SCM feasibility as opposed to explicitly evaluating competing scenarios for maximizing reductions in E.

Step 4: monitor and evaluate success

Changes in geomorphic trajectories (or lack thereof) were assessed using a weight of evidence approach, including pre/post-intervention cross section surveys, photos, and field observations at control and experimental reaches. Assessment of CEM Stage is commonly included in geomorphic field assessments (Simon and Downs 1995; Bledsoe et al. 2012) and can be reinforced with time-series cross section data (e.g. Hawley et al. 2020). Observations also included biological data (presence/absence of bank/bar vegetation, fish, etc.), wood retention, habitat assessments, etc. (e.g.

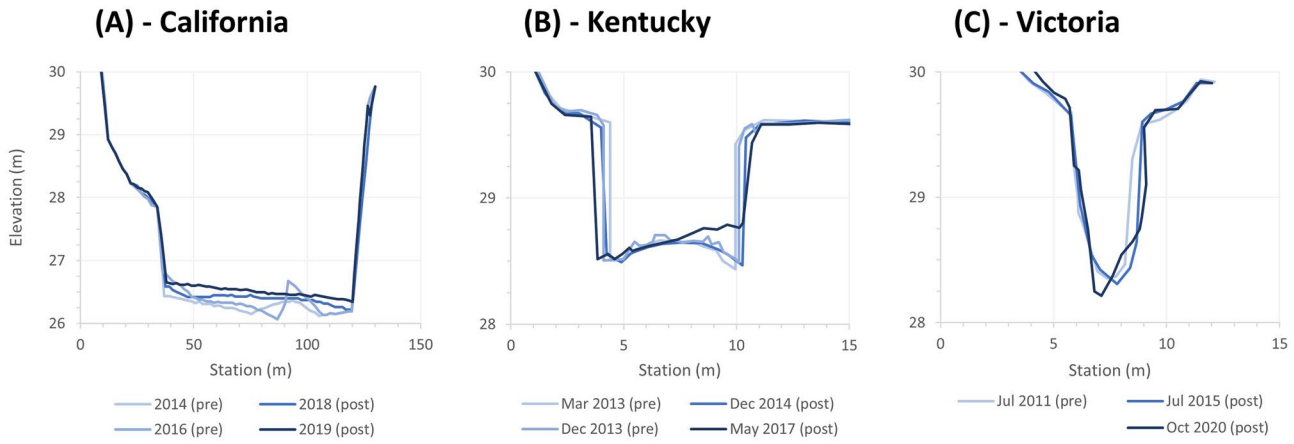


Fig. 4 Time series cross section surveys at intervention sites in California (**A**), Kentucky (**B**), and Victoria (**C**)

Hawley 2021). Based on the weight of evidence, has the post-intervention stream substantially changed its geomorphic trajectory relative to the pre-intervention condition?

In California, the application of the E framework to the SCM designs at the greenfield development site (5% TIA)—matching the predeveloped sediment transport capacity (E = 1) has appeared to maintain a trajectory of geomorphic recovery in the receiving stream at both downstream monitoring locations. Following the construction of the development and basin, the aggradational trajectory, CEM Stage 4, continued at both monitoring sites: the wide unconfined "CA 1" (Fig. 4A) and the more defined downstream site "CA 2", with no perceptible changes in the vegetated channels. In contrast, cross section data showed the entrenched upstream control site following a trajectory of incision, CEM Stage 2, and erosion of the left toe during the post-development period that may be attributed to historic cattle grazing and ranch operations over the last 60 years. Although the irrigation runoff and legacy impacts from historic grazing confound our ability to draw definitive conclusions at this case study location, the lack of visibly apparent downcutting, bank erosion, and channel widening at the downstream monitoring locations, despite having 7 events that exceeded the 3-month, 1-h storm in the post-development period (compared to 6 events in the pre-developed period over equal time periods of ca. 3 years), in contrast to the continued signs of instability at the upstream site underscores the importance of the SCM on minimizing E. Moreover, these observations are a sharp contrast from the types and extents of channel enlargement that used to be commonplace downstream of greenfield developments in this region prior to the implementation of hydromodification management SCMs (e.g. see Hawley and Bledsoe (2013) or Taniguchi and Biggs (2015)) where incision has even been observed in previously aggradational reaches (Hawley et al. 2012).

For Kentucky, the stormwater retrofit that used the E framework to discharge a less erosive flow regime appears to have induced a trajectory of geomorphic recovery in the formerly unstable receiving streams. The immediate receiving stream (Spur) and DS Site (Figs. 4B, 5) have experienced notable improvements in geomorphic stability, habitat, and flow, whereas the control site has continued on a degradational trajectory over the same time period (Hawley 2021). The site in the immediate receiving stream also now supports fish in several pools in a reach that used

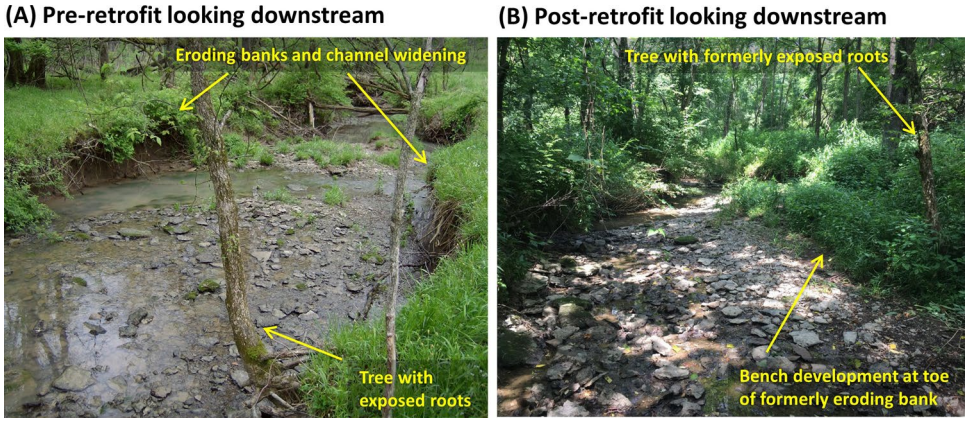


Fig. 5 Kentucky case study photo of pre-retrofit channel with eroding banks on 29 April 2013 (**A**) and post-retrofit channel with a vegetated bench and more stable banks on 8 July 2019 ~ 5.5 years after the stormwater retrofit installation (**B**). Both photos are looking downstream at monitoring cross section from Fig. 4B (the same tree on the right bank is in both photos)

to go dry ~ 10% of the time prior to the retrofit installation (Hawley 2018). Cross section data at the downstream site showed a shift from CEM Stage 3 to Stage 4 in the first ~ 3.5 years following the retrofit (Fig. 4B) that coincided with additional failure of both banks and bar building along the toe of the right bank (Hawley et al. 2020; Hawley 2021). The colonization of the bars by vegetation ~ 2 years later (~ 5.5 years following retrofit installation) is indicative of a potential transition to CEM Stage 5 (Fig. 5). The establishment of permanent (woody) vegetation along with additional years of cross-section monitoring documenting an equilibrium channel would add confidence to the CEM Stage 5 (recovered) classification. A competing hypothesis that the observed geomorphic trajectory was attributable to precipitation changes was not supported. The post-retrofit period of 5 years and 8 months had 16 events that exceeded the 3-month, 1-h storm compared to just 10 events over the comparable pre-retrofit period. Prior to the retrofit, the 3-month event exceeded $Q_{critical}$, suggesting that without the retrofit the slumped material from bank erosion would have likely been washed away and not colonized by vegetation.

In the Victoria case study E was not reduced by the distributed SCMs in the previously developed (14% TIA) watershed over the study period. The "post-retrofit" period showed a 13% increase in E relative to the "during retrofit" period as standardized by the sediment transport capacity in the reference catchment over the same time periods (Table 2). Comparison with a control catchment, where E increased 68% over the same period, suggests that the stormwater interventions had an attenuating effect on some flows that would have otherwise contributed to erosion. Furthermore, the "post-retrofit" periods had a reduced frequency of channel-eroding events that was attributable to changes in precipitation (e.g. the exceedance frequency of the 3-month storm changed from 4.1 events per year during intervention to 3.6 events per year post-intervention). However, the stormwater intervention and rainfall effects together did not induce a trajectory of geomorphic recovery in the receiving stream network within the ~ 5-year post-intervention monitoring period. Although it is feasible that the stormwater interventions could help to facilitate a trajectory of geomorphic recovery in the future, survey data (Fig. 4C), photographs (Fig. 6), and subsequent field assessments suggest that the channel is still experiencing a degradational trajectory including downcutting, bank failure, and channel widening (CEM Stage 3).

Discussion

The case studies presented here indicate that SCMs that focus on managing sediment transport capacity and reducing E can be effective at maintaining/inducing trajectories of geomorphic recovery. These examples contrast with the geomorphic instability that is abundantly documented in channels downstream of conventional stormwater management approaches that do not explicitly attempt to maintain/restore predeveloped sediment transport capacity (e.g. Figure 7; Booth and Jackson 1997; MacRae 1997; Vietz et al. 2014). The E-based design at the greenfield development in southern California appears to have maintained the aggradational trajectory at the monitoring location that was occurring prior to development. Similarly, the Kentucky retrofit of the conventional detention basin to decrease the freeboard to the spillway by 21 cm for the 100-yr design storm in order to restrict the erosive discharges of more frequent storms (e.g. 3-month, 6-month, and 1-year events) reduced E by 42% and coincided with a shift from a degradational trajectory prior to the retrofit to an aggradational/recovering trajectory post-retrofit. By contrast, the distributed SCMs that were retroactively installed in a previously developed watershed in Australia that lacked transport-capacity-based controls did not appear to coincide with a shift in the degradational geomorphic trajectory in the fine-grained stream.

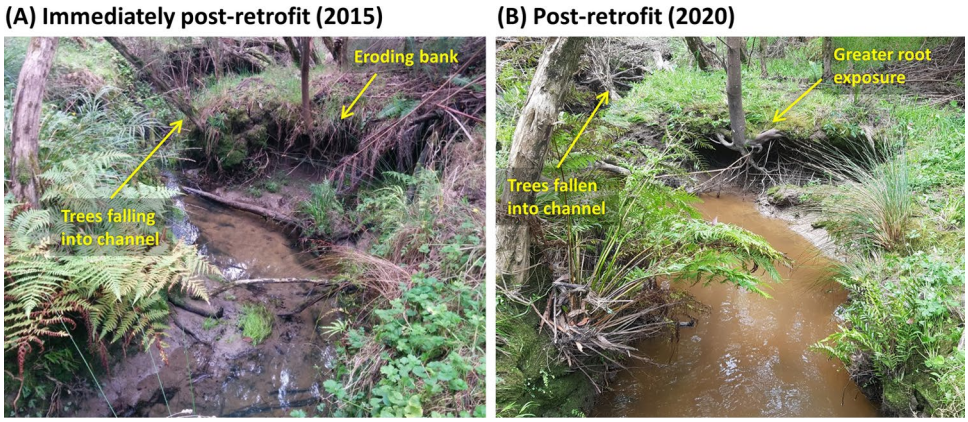


Fig. 6 Victoria case study photo of immediately post-retrofit channel with eroding banks on 9 July 2015 (**A**) and 6-years post-retrofit channel with continued bank erosion and incision into the clay bedrock on 28 October 2020 (**B**). SCMs were mostly installed between 2010 and 2014. Both photos are at the monitoring cross section from Fig. 4C



Fig. 7 Typical southern California example of incision and bank failure observed in fine-grained channels downstream of conventional development (27% TIA, developed in the 1980's) that lack stormwater intervention tailored at reducing sediment transport capacity

How much E reduction is necessary?

The extent of E reduction necessary to facilitate geomorphic recovery likely depends on the hydrogeomorphic context of the setting. For example, all else being equal, coarse grained channels may be more resilient than fine-grained channels, and less entrenched channels may be more resilient than more entrenched channels. Using a dataset of 84 sites in southern California, Hawley and Bledsoe (2013) used logistic regression analysis to show that the risk of channel enlargement decreases with bed material size (Fig. 8). Just as coarse bed material can provide a degree of resistance to channel instability in some urban streams (e.g. Booth 1990; Booth and Henshaw 2001; Hawley and Bledsoe 2013; Taniguchi and Biggs 2015; Bledsoe et al. 2016; Utz et al. 2016), coarser-bedded streams may be able to facilitate a return to equilibrium at E values greater than 1, as was observed in the Kentucky case study.

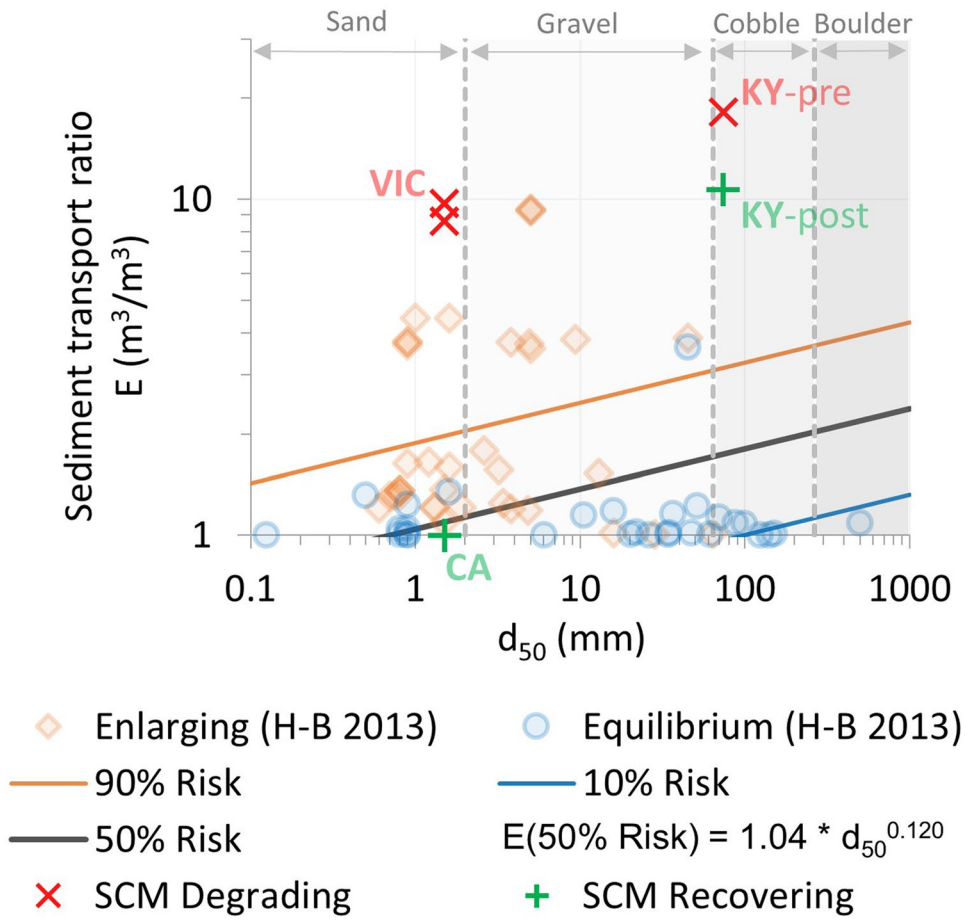


Fig. 8 The risk of channel enlargement increases with the sediment transport capacity ratio (E) and decreases with the median particle size (d50), adapted from Hawley and Bledsoe (2013)

The extent of channel adjustment prior to the stormwater intervention will likely affect the extent and timeframe of the geomorphic recovery. Coarse, entrenched channels that are already fairly wide (e.g. CEM stage 3 or 4) may be more primed for a recovery in response to geomorphically-meaningful stormwater interventions. Other more susceptible settings such as entrenched (CEM stage 2), fine beds (e.g. Bledsoe et al. 2012), and/or streams with disconnected/variable sediment supplies (e.g. Wolman 1967; Russell et al. 2017) may not immediately transition to a recovery trajectory even with a 100% reduction in excess sediment transport capacity, underscoring the importance of channel hydraulics (Anim et al. 2019) among other factors. This may also help to explain why the Kentucky stream appeared to recover at higher E values than would be expected from previous work (10.7 as opposed to ~ 2 for a 74-mm d_{50}; Fig. 8). More data across more levels of E and sediment size are clearly needed, but bed coarsening (Robinson 1976; Hawley et al. 2013; Russell et al. 2018), channel widening (Hammer 1972; Pizzuto et al. 2000; Bevan et al. 2018; Hawley et al. 2020) and channel headcutting and the associated decreases in slope (Schumm et al. 1984; Hawley et al. 2012; Taniguchi et al. 2018; Sullivan et al. 2020) are all channel adjustment mechanisms that systematically work to dissipate the excess erosive energy of the flow regime and/or increase the resistance of the setting (Lane 1955; Hawley 2018).

The selection of reference conditions also plays a role in the use and interpretation of the E framework. Where the reference condition is a pre-developed flow regime in a channel that has already partially adjusted (e.g. Kentucky), the erosion potential may be overestimated, relative to an approach that compares to a pre-developed flow in a pre-developed channel (e.g. Victoria). However, the Victoria approach of using a nearby undeveloped channel as a surrogate pre-developed channel presents its own challenges in understanding and minimizing the effect of context (e.g. slope, geology, climate) when selecting a suitable reference site. Additionally, it is important to note how the pre-developed transport capacity is defined in different regulatory settings. In California, the predevelopment transport capacity, which SCMs from new development are required to match, is the transport capacity prior to the new development, which in many cases are far from the reference transport capacity. The California greenfield case study, herein, illustrates a less common example of new development in a predominantly open-space watershed where predevelopment conditions are closer to reference. It is possible that California hydromodification requirements in more urbanized watersheds with channels that are actively eroding, CEM stage 2 or early stage 3, may need to be more stringent to further minimize E and induce a recovering trajectory if that is the desired stakeholder outcome.

The relative change in E may also be important in interpreting these case studies: E of 10.7 in Northern Kentucky represented a 42% improvement relative to the pre-retrofit condition (E = 18.2), whereas E in Victoria was similar pre and post-retrofit (with effects of mitigation and rainfall variability largely cancelling each other out). Importantly, although the Northern Kentucky case study appears to be on a trajectory of geomorphic recovery, it is unlikely to return to the size and shape of its predevelopment form. It can be safely inferred based on a 10-year study at 61 sites (Hawley et al. 2020) that the channel had already undergone considerable widening such that the resulting equilibrium form induced by the retrofit will likely be a larger channel than the predeveloped stream. In retrofit situations, where reducing E to one is often not practical, a substantial but non-complete reduction in E is still likely to improve physical form and functioning. Effects of such interventions are expected to be most visible in streams that are already near recovery thresholds (e.g. late CEM Stage 3 or Stage 4; Kentucky), as opposed to more actively eroding streams (e.g. CEM Stage 2 or early Stage 3; Victoria) that may take much longer to facilitate a transition to recovery stages.

The extent of impervious area (Booth and Jackson 1997; Bledsoe and Watson 2000), timing (Leopold et al. 2005; Chin et al. 2017), and existing SCM treatment (Hopkins et al. 2020), along with the hydrogeomorphic setting (Booth et al. 2016) and other natural and anthropogenic factors (Utz et al. 2016) are also likely to play a role in the extent of E reduction that is necessary to facilitate geomorphic recovery. Although the E framework offers an attempt to account for the influence of impervious area, existing SCMs, and other factors in its hydrologic and sediment transport modeling steps, these case studies all had relatively low levels of watershed imperviousness (< 15% TIA). Additional data is needed to evaluate the efficacy of the E framework in watersheds with larger amounts of TIA, old vs. young development, and different levels of and types of SCM treatments. For example, a high TIA watershed with extensive coverage of SCMs may need relatively lower reductions in E than a lower TIA watershed that had no SCMs. At the same time one can also envision cases where century(ies)-old developed watersheds with no SCMs needing even less reduction in E due to the channel having already undergone substantial self-adjustment.

The role of disturbance frequency

The frequency of disturbance events may also be an important mechanism to consider in the E framework, particularly given the importance of the stabilizing role of vegetation in facilitating the transition from CEM Stage 4 to 5 in the Schumm et al. (1984) model. For example, the Kentucky retrofit reduced the frequency of $Q_{critical}$ exceedance from the 3-month design

storm under pre-retrofit conditions to the 2-year storm under post-retrofit conditions (Hawley et al. 2017). The ~ eightfold improvement in lag between disturbance events was likely an important driver in facilitating vegetation colonization that transformed the formerly unstable bars into stable benches. The mechanistically based approach in this comparative study could therefore be extended beyond just total transport capacity by considering feedback between seasonality and frequency of disturbance events and vegetation growth. Incorporating disturbance frequency into the E framework may be particularly important for macroinvertebrate communities (Poff 1992; Holomuzki and Biggs 2000; Hawley et al. 2016; Jordt and Taylor 2021) in the context of climate change with more intense precipitation events and more prolonged droughts expected in many regions (Hidalgo et al. 2009; Stocker 2014; Kundzewicz et al. 2018; Swain et al. 2018). Both field (Masteller et al. 2019) and flume (Masteller and Finnegan 2017) research suggests that the entrainment threshold for a given stream can change based on the frequency of disturbance, with more time between disturbance events coinciding with riverbed armoring and higher thresholds for bed mobility.

Setting expectations for (at least some) additional erosion

A final point to underscore is the importance of setting reasonable expectations with the E framework, including the role of additional erosion in bearing out potential geomorphic recoveries. As indicated by Fig. 1, an entrenched channel likely needs to become over-widened (CEM Stage 4) prior to being able to transition to a recovered state (CEM Stage 5). Stormwater interventions that facilitate transitions from degradational (CEM Stages 2 and 3) to aggradational (CEM Stage 4) channels will in most cases coincide with at least a temporary increase in channel widening. This is not only underscored by the Kentucky case study presented herein (e.g. note the widening in Fig. 4B), but is also consistent with longer term studies which document the highest rates of widening during CEM Stage 4 when large sediment bars deflect flow into already unstable banks that are prone to additional failure. In a 10-year study at 61 sites, Hawley et al. (2020) documented average rates of widening of 17 cm/yr for CEM Stage 4, compared to 9 cm/yr for Stage 3 and just 0.3 cm/yr for Stage 2. Furthermore, settings with fast-growing vegetation may facilitate quicker recoveries than in semiarid or arid channels. El Nino cycles, drought, fires, and changes in irrigation runoff, among other factors, can also affect the speed and styles of geomorphic recovery (or lack thereof). All of this reinforces the challenges associated with assessing and monitoring complex channel responses and the value of having long-term datasets when evaluating the geomorphic effects of hydrologic restoration interventions such as those designed with the E framework.

Although post-intervention data for geomorphically-effective stormwater interventions are rare, the case studies herein are consistent with well-established principles of river mechanics (e.g. Biedenharn et al. 2001; Wolman and Miller 1960), suggesting that the excess sediment transport capacity of the post-developed regime is a degradational mechanism that must be sufficiently managed if equilibrium channels are a goal. Using the E framework to guide and optimize SCM design and watershed-scale hydrologic restoration may facilitate more meaningful improvements in geomorphic integrity relative to management approaches that do not explicitly account for sediment transport capacity.

Limitations and next steps

The framework and case studies presented here underscore the need for more geomorphic data downstream and upstream of retrofits and/or greenfield developments that are intended to restore/maintain geomorphic equilibrium. Longer-term datasets and more standardized data collection across a gradient of channel and watershed conditions, perhaps collected by regional entities as opposed to representatives of individual projects, could facilitate more objective assessments of the efficacy of SCM designs that minimize E and synthesize regional hydromodification management beyond the project scale. The E framework could also benefit from consistency regarding what "predevelopment" implies (e.g. conditions immediately prior to the latest development vs. no imperviousness vs. pre European settlement).

The E approach could be further evaluated via other regionally-appropriate hydrologic, water quality, and ecological metrics to document improvement or lack thereof in other facets of stream condition. For example, if interventions can facilitate a more natural streambed disturbance regime, are there corresponding signs of recovery in the macroinvertebrate community? Baseflow restoration in humid settings with a history of anthropogenic drainage efforts could be another sign of ecological recovery, whereas artificially prolonged flows in dryland channels could close off channels via vegetation encroachment (e.g. CEM Phase 1Veg in the Hawley et al. (2012) model that was also apparent in the California case study included herein downstream of an orchard). Perennialization is also a potential issue in Melbourne streams (Duncan et al. 2014), which could facilitate invasion by species suited to perennial streams, displacing ephemeral specialists. A functional flows approach (e.g. Yarnell et al. 2020) allows managers to target multiple aspects of the annual hydrograph that are tied to ecological, geomorphic, and biogeochemical functions/processes. As with all elements of stream management, we recommend that managers use the E framework as one aspect of stream

management, placed in proper context alongside other stakeholder and ecological management goals for urban streams (e.g. Bixler et al. 2021).

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Data availability Comparative study data provided in the tables and figures within the manuscript. More detailed data and analysis provided in previously published materials cited within this manuscript.

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References

Anim DO, Fletcher TD, Pasternack GB, Vietz GJ, Duncan HP, Burns MJ (2019) Can catchment-scale urban stormwater management measures benefit the stream hydraulic environment?: J Environ Manag 233(1):1–11

Arizona Department of Water Resources (1985) Design Manual for Engineering Analysis of Fluvial Systems. Arizona Department of Water Resources

Bevan V, MacVicar B, Chapuis M, Ghunowa K, Papangelakis E, Parish J, Snodgrass WJ (2018) Enlargement and evolution of a semi-alluvial creek in response to urbanization. Earth Surf Proc Land 43(11):2295–2312

Biedenharn DS, Elliott CM, Watson CC (1997) The WES Stream Investigation and Streambank Stabilization Handbook: U.S. Army Engineer Waterways Experiment Station

Biedenharn DS, Thorne CR, Soar PJ, Hey RD, Watson CC (2001) Effective discharge calculation guide. Int J Sedim Res 16(4):445–459

Bixler P, Belaire A, Faust K, Scoggins, Gonzales A (2021) Exploring the connection between transdisciplinary co-production and urban stream sustainability solutions: A case study at an urban stream management symposium. Urban Ecosyst

Bledsoe BP (2002) Stream erosion potential associated with stormwater management strategies: J Water Resour Plan Manag 128:451–455

Bledsoe BP, Baker DW, Nelson PA, Rosburg T, Sholtes J, Stroth TR (2016) Design hydrology for stream restoration and channel stability at stream crossings: Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine, National Cooperative Highway Research Program (NCHRP) Project 24–40

Bledsoe BP, Stein ED, Hawley RJ, Booth DB (2012) Framework and tool for rapid assessment of stream susceptibility to hydromodification. J Am Water Resour Assoc 48(4):788–808

Bledsoe BP, Watson CC (2000) Observed thresholds of stream ecosystem degradation in urbanizing areas: a process-based geomorphic explanation, in Flug, M. a. F., D., ed., Watershed management. Science and Technology for the New Millennium, American Society of Civil Engineers

Booth DB (1990) Stream-channel incision following drainage-basin urbanization. Water Resour Bull 26(3):407–417

Booth DB, Fischenich CJ (2015) A channel evolution model to guide sustainable urban stream restoration. Area 47(4):408–421

Booth DB, Henshaw PC (2001) Rates of channel erosion in small urban streams, in Wigmosta, M. S., ed. Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas, Volume AGU Monograph Series, Water Science and Application 2:17–38

Booth DB, Jackson CR (1997) Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation: J Am Water Resour Assoc 33(5):1077–1090

Booth DB, Roy AH, Smith B, Capps KA (2016) Global perspectives on the urban stream syndrome: Freshwater. Science 35(1):412–420

Bunte K, Abt SR (2001) Sampling frame for improving pebble count accuracy in coarse gravel-bed streams. J Am Water Resour Assoc 37(4):1001–1014

Cain A, Iannetta M, Muirhead C, Papangelakis E, Raso T, MacVicar B, Ashmore P (2020) Tracking the mean annual velocity and vertical mixing of bedload tracers, in Uijttewaal W, Franca MJ, Valero D, Chavarrias V, Arbós CY, Schielen R, Crosato A River Flow 2020: Proceedings of the 10th Conference on Fluvial Hydraulics (Delft, Netherlands, 7–10 July (2020): Delft, Netherlands, Taylor & Francis Group, p. 371–380

Chin A (2006) Urban transformation of river landscapes in a global context. Geomorphology 79(3–4):460–487

Chin A, Gidley R, Tyner L, Gregory KJ (2017) Adjustment of dryland stream channels over four decades of urbanization: Anthropocene 20:24–36

County of Orange (2011) South Orange County hydromodification management plan. 91 pp. Available: https://www.waterboards.ca.gov/rwqcb9/water_issues/programs/stormwater/docs/oc_permit/updates_031212/South_Orange_County%20HMP.pdf

Duncan JM, Wright SG, Brandon TL (2014) Soil strength and slope stability. John Wiley & Sons

Einstein HA (1942) Formulas for the transportation of bed load: Trans Am Soc Civil Eng 107:561-573

Galster JC, Pazzaglia FJ, Germanoski D (2008) Measuring the impact of urbanization on channel widths using historic aerial photographs and modern surveys. J Am Water Resour Assoc 44(4):948–960

Gomez B (1991) Bedload transport: Earth-Science Reviews 31(2):89–132

Hammer TR (1972) Stream channel enlargement due to urbanization: Water Resour Res 8:139–167

Harrelson CC, Rawlins CL, Potyondy JP (1994) Stream channel reference sites: an illustrated guide to field technique, in U. S. Department of Agriculture, F. S., Rocky Mountain Forest and Range Experiment Station, ed., Volume Gen Tech Rep RM-245: Fort Collins CO p61

Harvey MD, Watson CC, Schumm SA, Channelized streams: An analog for the effects of urbanization, in Proceedings, (1983) International Symposium on Urban Hydrology. Hydraulics and Sediment Control, University of Kentucky, Lexington, Kentucky 1983:401–410

Hawley RJ (2018) Making stream restoration more sustainable: A geomorphically, ecologically, and socioeconomically principled approach to bridge the practice with the science: BioScience 68(7):517–528

Hawley RJ (2021) Expanding catchment-scale hydrologic restoration in suburban watersheds via stream mitigation crediting—A Northern Kentucky (USA) case study: Urban Ecosystems. https://doi.org/10.1007/s11252-021-01139-x

Hawley RJ, Bledsoe BP (2011) How do flow peaks and durations change in suburbanizing semi-arid watersheds? A Southern California Case Study: Journal of Hydrology 405(1–2):69–82

Hawley RJ, Bledsoe BP (2013) Channel enlargement in semi-arid suburbanizing watersheds: a southern California case study. J Hydrology 496:17–30

Hawley RJ, Bledsoe BP, Stein ED, Haines BE (2012) Channel evolution model of semiarid stream response to urban-induced hydromodification. J Am Water Resour Assoc 48(4):722–744

Hawley RJ, Goodrich JA, Korth NL, Rust CJ, Fet EV, Frye C, MacMannis KR, Wooten MS, Sinha R (2017) Detention outlet retrofit device improves the functionality of existing detention basins by reducing erosive flows in receiving channels. J Am Water Resour Assoc 53(5):1032–1047

Hawley RJ, MacMannis KR, Wooten MS (2013) Bed coarsening, riffle shortening, and channel enlargement in urbanizing watersheds, northern Kentucky, U.S.A.: Geomorphology 201:111–126.

Hawley RJ, MacMannis KR, Wooten MS, Fet EV, Korth NL (2020) Suburban stream erosion rates in northern Kentucky exceed reference channels by an order of magnitude and follow predictable trajectories of channel evolution: Geomorphology 352:106998

Hawley RJ, Vietz GJ (2016) Addressing the urban stream disturbance regime: Freshwater. Science 35(1):278–292

Hawley RJ, Wooten MS, MacMannis KR, Fet EV (2016) When do macroinvertebrate communities of reference streams resemble urban streams? The Biological Relevance of Qcritical: Freshwater Science 35(3):778–794

Hidalgo HG, Das T, Dettinger M, Cayan D, Pierce D, Barnett T, Bala G, Mirin A, Wood A, Bonfils C (2009) Detection and attribution of streamflow timing changes to climate change in the western United States. J Clim 22(13):3838–3855

Hollis GE, Luckett JK (1976) The response of natural river channels to urbanization: Two case studies from southeast England. J Hydrol 30(4):351–363

Holomuzki JR, Biggs BJF (2000) Taxon-specific responses to high-flow disturbance in streams: implications for population persistence. Journal North Am Benthologic Soc 19(4):670–679

Hopkins KG, Bhaskar AS, Woznicki SA, Fanelli RM (2020) Changes in event-based streamflow magnitude and timing after suburban development with infiltration-based stormwater management. Hydrol Process 34(2):387–403

Jordt S, Taylor BW (2021) A rolling stone gathers no eggs: the importance of stream insect egg laying natural history for stream restoration. Ecology 102(7):e03331

Kundzewicz Z, Krysanova V, Benestad R, Hov Ø, Piniewski M, Otto I (2018) Uncertainty in climate change impacts on water resources. Environ Sci Policy 79:1-8

Lane EW (1955) The importance of fluvial morphology in hydraulic engineering: Proceedings. ASCE 81(745):1–17

Leopold LB, Huppman R, Miller A (2005) Geomorphic effects of urbanization in forty-one years of observation. Proc Am Philos Soc 149(3):349–371

MacRae CR (1991) A procedure for design of storage facilities for instream erosion control in urban streams. Doctoral: University of Ottawa

MacRae CR (1993) An alternate design approach for the control of instream erosion potential in urban watersheds, in Proceedings Urban Storm Drainage: Proceedings of the Sixth International Conference, Niagra Falls, Ontario, Canada, September 12–17, 1993 1993, Volume 2, IAHR/IAWQ Joint Committee on Urban Storm Drainage, p. 1086–1091

MacRae CR (1997) Experience from morphological research on Canadian streams: Is the control of the two-year frequency runoff event the best basis for stream channel protection?, in Roesner, L. A., ed. Effects of Watershed Development and Management of Aquatic Ecosystems: New York, ASCE, p. 144–162

Masteller CC, Finnegan NJ (2017) Interplay between Grain Protrusion and Sediment Entrainment in an Experimental Flume: Journal of Geophysical Research: Earth Surface 122(1):274–289

Masteller CC, Finnegan NJ, Turowski JM, Yager EM, Rickenmann D (2019) History-Dependent Threshold for Motion Revealed by Continuous Bedload Transport Measurements in a Steep Mountain Stream. Geophys Res Lett 46(5):2583–2591

Meyer-Peter E, Müller R (1948) Formulas for bed-load transport, in proceedings Proc. 2nd Meeting International Association for Hydraulic Research, Stockholm, p. 39–64

Papangelakis E, MacVicar B, Ashmore P (2019) Bedload sediment transport regimes of semi-alluvial rivers conditioned by urbanization and stormwater management. Water Resour Res

Paul MJ, Meyer JL (2001) Streams in the urban landscape: Annual Rev Ecol Syst 32:333–365

Peel MC, Finlayson BL, McMahon TA (2007) Updated World Map of the Köppen-Geiger Climate Classification: Hydrology and Earth System Sciences Discussions 4(2):439–473

Phillips B, Austin, L, Chapman R (2013) Comprehensive Regional Stormwater Plan: Ranch Plan Planned Community Runoff Management Plan (PACE JN 8649E). Pacific Advanced Civil Engineering, Inc.

Pizzuto JE, Hession WC, McBride M (2000) Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology 28(1):79–82

Poff NL (1992) Why disturbances can be predictable: A perspective on the definition of disturbance in streams. J North Am Benthological Soc 11:86–92

Polvi LE, Lind L, Persson H, Miranda-Melo A, Pilotto F, Su X, Nilsson C (2020) Facets and scales in river restoration: Nestedness and interdependence of hydrological geomorphic, ecological, and biogeochemical processes: J Environ Manag 265:110288

Robinson AM (1976) The effects of urbanization on stream channel morphology, Proceedings of the National Symposium on Urban Hydrology, Hydraulics, and Sediment Control: Lexington, Kentucky, University of Kentucky

Rosburg TT, Nelson PA, Bledsoe BP (2017) Effects of Urbanization on Flow Duration and Stream Flashiness: A Case Study of Puget Sound Streams. Western Washington, USA: JAWRA Journal of the American Water Resources Association 53(2):493–507

Russell KL, Vietz GJ, Fletcher TD (2017) Global sediment yields from urban and urbanizing watersheds: Earth Sci Rev 168:73–80

Russell KL, Vietz GJ, Fletcher TD (2018) Urban catchment runoff increases bedload sediment yield and particle size in stream channels: Anthropocene 23:53–66

Russell KL, Vietz GJ, Fletcher TD (2020) How Urban Stormwater Regimes Drive Geomorphic Degradation of Receiving Streams: Progress in Physical Geography: Earth and Environment 44(5):746–778

Schumm SA, Harvey MD, Watson CC (1984) Incised channels: Morphology, Dynamics, and Control. Colorado, Water Resources Publications, Littleton

Simon A, Downs PW (1995) An interdisciplinary approach to evaluation of potential instability in alluvial channels. Geomorphology 12:215–232

Simon A (1989) A model of channel response in disturbed alluvial channels. Earth Surf Process Landf 14(1):11–26

Simon A, Klimetz L (2008) Relative magnitudes and sources of sediment in benchmark watersheds of the Conservation Effects Assessment Project. J Soil Water Conserv 63(6):504–522

Simon A, Rinaldi M (2000) Channel instability in the loess area of the midwestern United States. J Am Water Resour Assoc 36(1):133–150

Simon A, Rinaldi M (2006) Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response: Geomorphology 79: 361–383

Somerville D, Pruitt B (2004) Physical stream assessment: A review of selected protocols for use in the Clean Water Act Section 404 Program: Prepared for the US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Wetlands Division (Order No. 3W-0503-NATX), Washington, DC

Spasojevic M, Holly FM (1994) Three-dimensional numerical simulation of mobile-bed hydrodynamics. Contract Rep. HL-94-2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Stein ED, Federico F, Booth DB, Bledsoe BP, Bowles C, Rubin Z, Kondolf GM, Sengupta A (2012) Hydromodification Assessment and Management in California: Southern California Coastal Water Research Project

Stocker T (2014) Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Stroth TR, Bledsoe BP, Nelson PA (2017) Full spectrum analytical channel design with the capacity/supply ratio (CSR): Water 9:4

Sullivan J, Grubb J, Willis R, Boozer D, Flickinger B, Dixon CE (2020) Cohesive Channel Response to Watershed Urbanization: Insights from the Sand River. Aiken SC: Water 12(12):3441

Swain DL, Langenbrunner B, Neelin JD, Hall A (2018) Increasing precipitation volatility in twenty-first-century California: Nature. Clim Change 8(5):427–433

Taniguchi KT, Biggs TW (2015) Regional impacts of urbanization on stream channel geometry: A case study in semiarid southern California: Geomorphology 28:228–236

Taniguchi KT, Biggs TW, Langendoen EJ, Castillo C, Gudino-Elizondo N, Yuan Y, Liden D (2018) Stream channel erosion in a rapidly urbanizing region of the US–Mexico border: documenting the importance of channel hardpoints with Structure-from-Motion photogrammetry. Earth Surf Process Landf 43(7):1465–1477

Trimble SW (1997) Contribution of stream channel erosion to sediment yield from an urbanizing watershed: Science 278:1442–1444

Utz RM, Hopkins K, Beesley L, Booth DB, Hawley RJ, Baker M, Freeman MC, Jones K (2016) Ecological resistance in urban streams: the role of natural and legacy attributes: Freshwater. Science 35(1):380–397

Van Rijn, LC (1984a) Sediment transport, part I: bed load transport. J Hydraulic Eng 110(10):1431–1456

Van Rijn, LC (1984b) Sediment transport, part II: suspended load transport. J Hydraul Eng 110(11):1613–1641

Vietz GJ, Sammonds MJ, Walsh CJ, Fletcher TD, Rutherfurd ID, Stewardson MJ (2014) Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness: Geomorphology 206:67–78

Walsh CJ, Burns MJ, Fletcher TD, Bos, DG, Kunapo J, Poelsma P, Imberger SJ (2021) Accepted. Linking stormwater control performance to stream ecosystem outcomes: incorporating a performance metric into effective imperviousness. PLoS Water. https://doi.org/10.31219/osf.io/mjz9h

Walsh CJ, Fletcher TD, Bos DG, Imberger SJ (2015) Restoring a stream through retention of urban stormwater runoff: a catchment-scale experiment in a social–ecological system: Freshwater Sci 34(3):1161–1168

Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan II RP (2005) The urban stream syndrome: current knowledge and the search for a cure: J North American Benthol Soc 24(3):706–723

Watson CC, Biedenharn DS, Bledsoe BP (2002) Use of incised channel evolution models in understanding rehabilitation alternatives. J Am Water Resour Assoc 38(1):151–160

White JY, Walsh CJ (2020) Catchment-scale urbanization diminishes effects of habitat complexity on instream macroinvertebrate assemblages: Ecol Appl v. n/a, no. n/a, p. e2199

Wilcock PR, Crowe JC (2003) Surface-based Transport Model for Mixed-Size Sediment. J Hydraul Eng 129(2):120–128

Wilcock PR, Kenworthy ST (2002) A two-fraction model for the transport of sand/gravel mixtures: Water Resour Res 38:10

Wilson GV, Periketi RK, Fox GA, Dabney SM, Shields Jr FD. Cullum RF (2007) Soil properties controlling seepage erosion contributions to streambank failure. Earth Surf Process Landf 32:447–459

Wolman MG (1967) A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler 49A:385–395

Wolman MG, Miller JP (1960) Magnitude and frequency of forces in geomorphic processes: J Geol 68:54–74

Wong M, Parker G (2006) Reanalysis and correction of bed-load relation of meyer-peter and müller using their own database. J Hydraul Eng 132(11):1159–1168

Yarnell SM, Stein ED, Webb JA, Grantham T, Lusardi RA, Zimmerman J, Peek RA, Lane BA, Howard J, Sandoval-Solis S (2020) A functional flows approach to selecting ecologically relevant flow metrics for environmental flow applications. River Res Appl 36(2):318–324

Yochum SE, Sholtes JS, Scott JA, Bledsoe BP (2013) 2017, Stream power framework for predicting geomorphic change: The. Colorado Front Range Flood: Geomorphology 292:178–192

Zeiger SJ, Hubbart JA (2019) Characterizing Land Use Impacts on Channel Geomorphology and Streambed Sedimentological Characteristics: Water 11(5):1088