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SPECIAL SECTION

SYSTEM-LEVEL NUTRIENT POLLUTION CONTROL STRATEGIES

Integrating Stormwater Management and Stream Restoration Strategies for Greater Water Quality Benefits

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Abstract

Urbanization alters the delivery of water and sediment to receiving streams, often leading to channel erosion and enlargement, which increases loading of sediment and nutrients, degrades habitat, and harms sensitive biota. Stormwater control measures (SCMs) are constructed in an attempt to mitigate some of these effects. In addition, stream restoration practices such as bank stabilization are increasingly promoted as a means of improving water quality by reducing downstream sediment and pollutant loading. Each unique combination of SCMs and stream restoration practices results in a novel hydrologic regime and set of geomorphic characteristics that interact to determine stream condition, but in practice, implementation is rarely coordinated due to funding and other constraints. In this study, we examine links between watershed-scale implementation of SCMs and stream restoration in Big Dry Creek, a suburban watershed in the Front Range of northern Colorado. We combine continuous hydrologic model simulations of watershed-scale response to SCM design scenarios with channel evolution modeling to examine interactions between stormwater management and stream restoration strategies for reducing loading of sediment and adsorbed phosphorus from channel erosion. Modeling results indicate that integrated design of SCMs and stream restoration interventions can result in synergistic reductions in pollutant loading. Not only do piecemeal and disunited approaches to stormwater management and stream restoration miss these synergistic benefits, they make restoration projects more prone to failure, wasting valuable resources for pollutant reduction. We conclude with a set of recommendations for integrated planning of SCMs and stream restoration to simultaneously achieve water quality and channel protection goals.

Core Ideas

- Stormwater control measures (SCM) and stream restoration can reduce channel erosion.
- SCMs alone reduced sediment and phosphorus loading more than stream restoration alone.
- Coordinating SCMs and restoration has the greatest positive impact.

The negative effect of urbanization on stream systems, the so-called "urban stream syndrome," is well known (Walsh et al., 2005b). A dominant cause of urban stream degradation is hydrologic alteration—larger runoff volumes and higher and more frequent peak flows all lead to channel bed and bank erosion (Leopold, 1968; Booth, 1990). Channel erosion threatens valuable infrastructure, degrades aquatic habitat, and can contribute significant amounts of pollution to streams, including eroded fine sediment and bound constituents such as phosphorus (Fox et al., 2016). This is in addition to the pollutants carried directly from urban runoff to the stream. Managing urban runoff to reduce hydrologic alteration, improve water quality, and prevent stream channel degradation is a significant challenge.

Stormwater management can mitigate some of urbanization's effects on hydrology, potentially increasing channel stability. In addition, urban stream restoration can directly improve channel stability by increasing erosion resistance. These two management approaches are tightly linked, but they are often designed and implemented independently.

Many urban stormwater management programs focus specifically on maintaining pre-development peak flow rates of large, less frequent storms (to reduce flood risk) and removing pollutants such as totals suspended solids, nitrogen, and phosphorus through the use of stormwater control measures (SCMs) (Burns et al., 2012). Properly designed, watershed-scale SCMs can restore pre-development in-stream hydraulics (Anim et al., 2019); however, few management programs specifically focus on controlling the frequency and duration of flows that most contribute to stream erosion potential. In mobile, sand bed streams, the critical discharge for bed sediment movement is low (Tillinghast et al., 2011), meaning controlling smaller, more frequent events is essential for limiting channel incision (Bledsoe, 2002). Furthermore, because of increased runoff volumes in urban watersheds, it may not be possible to control erosion in these sensitive stream types if runoff volumes are not reduced (Rohrer and Roesner, 2006; Pomeroy et al., 2008; Elliott et al., 2010; Tillinghast et al., 2012; Anim et al., 2019). These previous studies showed that urban stream channels are sensitive to changes in a variety of flows across the flow duration curve, but they primarily looked at bed material transport as an indicator of channel stability. In fact, urban channels

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Abbreviations: BSTEM, Bank Stability and Toe Erosion Model; DEM, digital elevation model; EURV, excess urban runoff volume; REM, River Erosion Model; SCM, stormwater control measures; SWMM, Storm Water Management Model.

can respond primarily by widening, and it is therefore important to consider the resistance of the most erodible component of the stream channel (e.g., bed or banks; Bledsoe, 2001).

Restoration of urban streams is increasing in popularity, often with the dual goals of increasing channel stability and improving water quality (Bernhardt et al., 2005). Although water quality benefits are less certain (Selvakumar et al., 2010), channel stabilization projects can successfully prevent bed and bank erosion (Ernst et al., 2012). Other projects, however, have struggled with stability (Miller and Kochel, 2010), potentially because altered urban flow regimes were not adequately accounted for. Stream restoration can increase the erosion resistance of channel bed and banks, whereas altering channel geometry can change how flow hydraulics are expressed (Anim et al., 2018). There is therefore a strong connection between SCMs to manage watershed hydrology and channel restoration to reduce erosion potential, but it is currently unclear how these practices should be integrated.

The objective of this paper is to determine how infiltration-based stormwater practices can be best coordinated with channel restoration projects to improve channel stability and reduce sediment and adsorbed phosphorus loading from channel erosion. We present a novel approach to explore these interactions. We couple continuous hydrologic simulations under different stormwater control scenarios with a new mechanistic model of channel evolution. Our stormwater control scenarios were designed per local regulations to manage the excess urban runoff volume (EURV), to mitigate the effects of urbanization across a range of precipitation event sizes. Our channel restoration scenarios included bank grading and stabilization that were targeted to reaches with high erosion potential. We examined both uncoordinated and coordinated implementation to determine how stormwater management can be best coupled to urban channel restoration.

Materials and Methods

Study Area

Big Dry Creek is a 280-km^2 watershed north of Denver, CO (Fig. 1). The watershed has a mix of land use, with primarily undeveloped prairie in the upper portion, urban land in the middle, and agricultural land in the lower third. The hydrology of the basin has been significantly affected by urbanization as well as water management for irrigation. A reservoir in the upper part of the watershed controls flows in the stream, and several diversions and irrigation return flows in the agricultural part of the watershed further complicated the hydrology. These hydrologic alterations have caused the channel to incise and have led to significant bank erosion.

The channel bed material is primarily sand and fine gravel. Streambank material is mostly clay and sandy clay loam. Recently, channel incision has slowed and the channel is adjusting primarily through bank erosion and lateral migration (Lammers and Bledsoe, 2019). Water quality in Big Dry Creek is poor, and phosphorus reduction efforts are underway as part of a total maximum daily load for the Barr–Milton watershed (Clary, 2017). Total phosphorus concentrations also regularly exceed proposed in-stream nutrient standards for the state of Colorado (Clary, 2017). The modeled portion of the watershed includes the part of the basin downstream of the reservoir Standley Lake to USGS Gage 06720820. Land use in this part of the watershed is primarily suburban and urban development with some areas of open space (Fig. 1).

Stormwater Modeling

Urban runoff and the impact of stormwater infrastructure was simulated using the Storm Water Management Model (SWMM) version 5.1.12 (Rossman, 2015). A calibrated SWMM model for the area of interest was obtained from a flood hazard study in the watershed (Wright Water Engineers, 2010). This SWMM model had been calibrated by adjusting characteristic subbasin width until model peak flow values for the 1% annual exceedance event in each subbasin were within 10% of independently verified values. Although SWMM was calibrated with a focus on flood flows, this should not substantially influence the results of our analysis, since we were interested in relative differences between our different simulations, rather than absolute values. The model was modified for this study to only include subbasins and outfalls that contributed runoff to Big Dry Creek between Standley Lake and USGS Gage 06720820 (Fig. 1). The final model contained 96 subbasins with a total area of 53.3 km^2 entering the stream at 14 outfalls.

Effects of SCMs were evaluated using a baseline SWMM model without any stormwater infrastructure and two different methods of applying SCMs across the subbasins (random and coordinated implementation, see “Modeled Scenarios” below for details). The SWMM scenarios simulated 20 yr of hourly rainfall (1986–2006) and monthly average evaporation data and used 2 yr (1984–1986) as a model spin-up period. Fifteen-minute hydrographs were produced for each of the 14 outfalls. These were aggregated to hourly mean hydrographs for use in the channel erosion modeling. Monthly average estimates of baseflow were calculated using the Eckhardt recursive digital filter method (Eckhardt, 2005) implemented in the Web-based Hydrograph Analysis Tool (Lim et al., 2005) (from USGS gage data, Station 06720820) and added to the stormflow hydrographs from SWMM. We used default parameters for perennial streams with porous aquifers. Although baseflows in urban areas can be complicated by reduced infiltration and leaking water infrastructure (Bhaskar et al., 2016), the Eckhardt filter method has been successfully applied in urban areas (Hubbart and Zell, 2013). Average monthly baseflow values were used to provide seasonal estimates of baseflow. Higher resolution (e.g., daily) baseflow estimates could be obtained from the USGS gage data but would not correspond to the hourly storm flow values from SWMM.

Infiltration practices (modeled as rain gardens in SWMM) were used to manage the stormwater throughout the subbasins, with the goal of reducing runoff volume. A unit rain garden was designed to treat the EURV generated from the impervious area of the subbasins. Managing the EURV is part of full-spectrum detention—a management strategy to restore the hydrologic regime for all storms after development. The EURV was calculated according to the guidance from the Urban Drainage and Flood Control District’s *Urban Storm Drainage Criteria Manual Volume II* (UDFCD, 2016). Each rain garden was sized to be able to treat the EURV from 2002 m^2 (0.5 acres) of impervious area. For each subbasin, the total number of rain gardens needed to treat the total impervious area was determined by dividing the total impervious area of the subbasin by the amount of impervious area each rain garden could treat. Percentage imperviousness for each subbasin was determined based on existing land use data and assumed levels of imperviousness for each land use category (Wright Water Engineers, 2010; see the supplemental material for details). A total of 1.2 km^2 (296 acres) of SCMs were required to

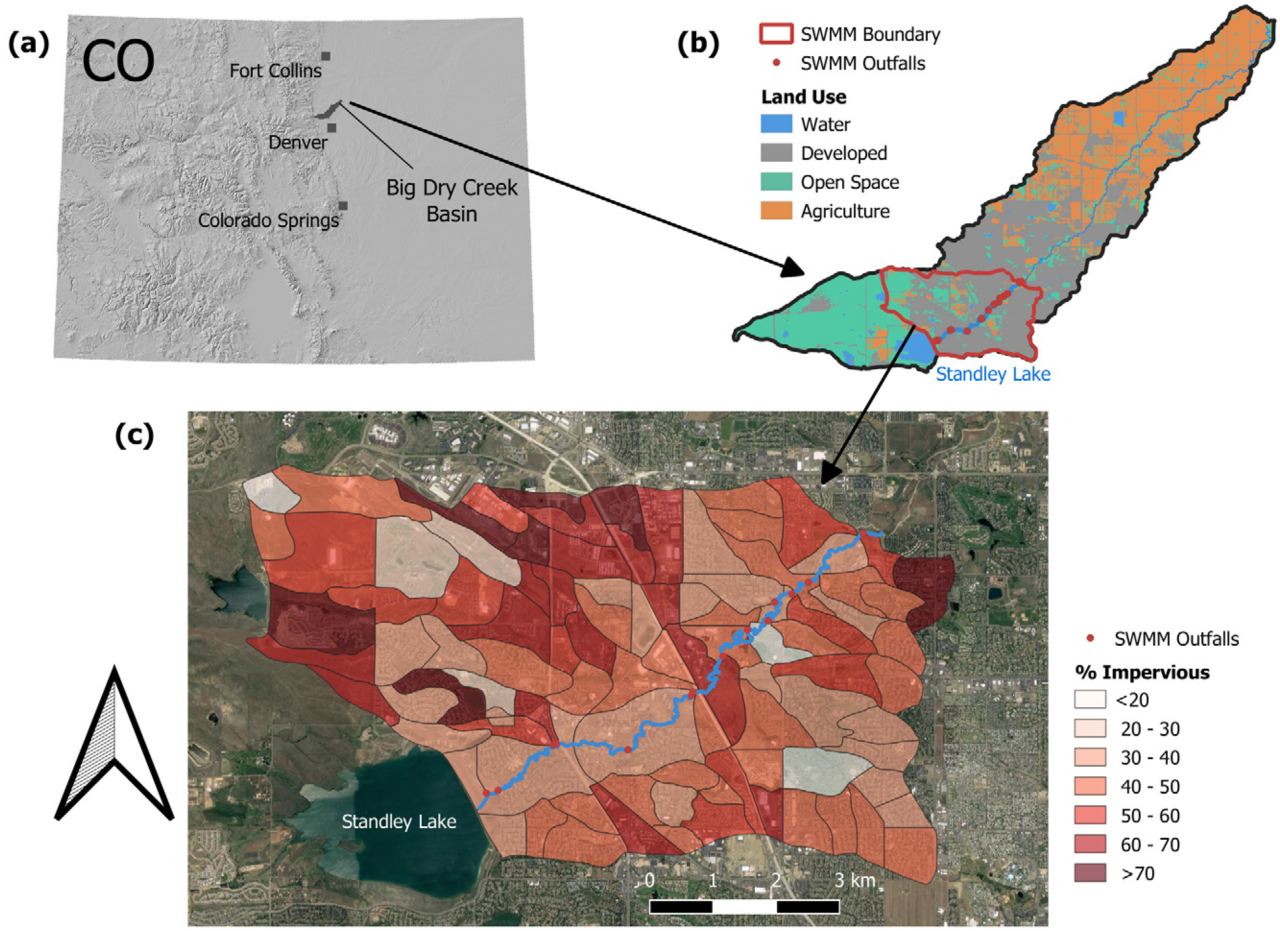

Fig. 1. (a) Location of study area in Colorado, (b) full Big Dry Creek watershed with 2011 National Land Cover Database (NLCD) (Homer et al., 2015) for reference, and (c) modeled subbasins in the Storm Water Management Model (SWMM) colored by percent impervious. Note that percentage impervious was based off local land use data and does not necessarily correspond to developed areas from NLCD. Map data 2015 Google.

manage the EURV for the study area. This amounts to ~2.2% of the total modeled area, with percentages ranging from 0.5 to 3.6% for individual subbasins.

Channel Erosion Modeling

We used the new River Erosion Model (REM) (Lammers and Bledsoe, 2018) to simulate channel evolution in 27 km of Big Dry Creek under different stormwater control and channel restoration scenarios. The REM mechanistically simulates changes in channel bed elevation by calculating sediment transport rates at subdaily time steps throughout the channel network. Specific stream power drives the model:

$$\omega = \gamma QS/w$$

where ω is specific stream power (W m^{-2}), γ is the specific weight of water (9810 N m^{-3}), Q is discharge (m^3 s^{-1}), S is channel slope (m m^{-1}), and w is water surface width (m). In addition to simulating changes in channel bed elevation, the REM also simulates channel widening from both fluvial erosion (using an excess shear stress approach) and bank failure (using a modified version of the Bank Stability and Toe Erosion Model [BSTEM]; Simon et al., 2000; Simon and Collison, 2001). Finally, REM can also simulate meander bend migration and associated lengthening of the stream channel. The REM calculates loading of fine sediment and any adsorbed phosphorus (given a user-inputed soil phosphorus concentration) from bank erosion. For more details on the model, see Lammers and Bledsoe (2018).

All REM inputs were obtained from Lammers and Bledsoe (2019). Readers are directed to that paper and the supplemental material for details on input data collection; only a brief explanation will be provided here. Channel longitudinal profiles and widths were obtained from a 0.75-m digital elevation model (DEM). Bank heights and angles were measured in the field. Bank soil total phosphorus concentrations were measured from 72 soil samples throughout the watershed. Soil cohesion was estimated based on logistic regression of bank heights and angles from stable and unstable banks (after Bledsoe et al., 2012), and bank critical shear stress was estimated based on gage flow data and estimates of bank erosion from aerial imagery. We ran 100 Monte Carlo simulations of REM, varying input parameters to obtain estimates of uncertainty associated with our results. Previous analysis of this model demonstrated that uncertainty bounds were not substantially different if >100 simulations were performed, but computational costs were much higher. A summary of model inputs is included in the supplemental material, including the inputs that were varied in the uncertainty analysis. All analyses of model results were performed in R version 3.5.1 (R Core Team, 2018).

Modeled Scenarios

We modeled combinations of three stormwater scenarios and three stream restoration scenarios (for a total of nine simulations). Stormwater scenarios included baseline (no stormwater infrastructure), "random" (installing stormwater controls in randomly selected subbasins), and "coordinated" (fully implemented stormwater control beginning with the most upstream basin and moving downstream) scenarios. For both the random and coordinated scenarios, stormwater infrastructure was implemented progressively every 5 yr over the 20-yr simulation period. In each 5-yr period, one quarter of the total of 1.2 km^2 (296 acres) of infiltration practices were installed.

Similarly, we modeled three different stream restoration scenarios: no restoration, "random" restoration (randomly selected stream reaches), and "coordinated" restoration (sequential restoration from upstream to downstream). For both restoration scenarios, we stabilized banks on approximately half (28/54) of the total number of 500-m-long reaches. Like the stormwater scenarios, we implemented restoration in 5-yr increments (seven reaches per period) over the entire 20-yr simulation. Restoration consisted of sloping banks back to 20°, adding bank armoring, and increasing bank cohesion. This is analogous to planting live willow (*Salix* spp.) stakes on the bank, which both increases the critical shear stress and (after roots are established) increases soil cohesion. For the first 5 yr after "restoration," the bank critical shear stress was increased to 23.9 Pa (~0.5 lb ft^{-2}). At the next 5-yr period (after the vegetation establishes), bank critical shear stress increased to 47.9 Pa (~1 lb ft^{-2}). These values are based on a collection of data summarized in NRCS (2007). After the first 5 yr, soil cohesion was increased to 4.4 kPa (base value of 1.4 kPa plus 3 kPa from root reinforcement). This added cohesion value came from modeling of two willow species in Colorado rivers using the Rip-Root module of BSTEM (Pollen-Bankhead and Simon, 2008; Polvi et al., 2014). If the banks erode (i.e., critical shear stress is exceeded) or fail despite this bank stabilization, the restoration practice is assumed to fail and bank critical shear stress and soil cohesion return to their default, unrestored values.

Results

The baseline stormwater scenario resulted in significantly higher phosphorus loading than either the random or coordinated stormwater scenarios (Fig. 2–3), regardless of the type of stream restoration applied. Without stream restoration, applying random or coordinated stormwater controls reduced pollutant loading by 70 and 76%, respectively (Table 1). Applying stream restoration to these two stormwater scenarios resulted in an additional 3 to 8% reduction in pollutant loads compared with the baseline, no restoration scenario. Coordinated restoration led to greater pollutant load reduction than random restoration.

Uncertainty in these estimates is high. When comparing distributions of cumulative phosphorus loads from all Monte Carlo simulations, only the scenarios with no restoration and coordinated restoration are significantly different (Fig. 3, $p <$ 0.05). When comparing all nine scenarios, the three baseline stormwater scenarios are all significantly different from the rest, whereas random and coordinated stormwater scenarios are all very similar. Only the coordinated stormwater–coordinated restoration scenario was significantly different from the random stormwater scenarios.

There was significant spatial variability in phosphorus loading rates along the modeled reach (Fig. 4–6), with the highest loading rates in the downstream half of the channel. There were also differences in the timing of erosion among the different modeled scenarios. Generally, the 0- to 5-yr period had the highest loading rates. For the baseline stormwater scenario, loading rates remained relatively constant over the course of the simulation. The random and coordinated stormwater simulations, however, showed drastic reductions in loading rates over time. This can also be seen in Fig. 2, where the cumulative loading levels out over time in the two scenarios with stormwater controls but increases at a relatively constant rate for the baseline simulation.

Figures 4 to 6 also show where stream restoration was applied over time for the different scenarios, as well as the probability of restoration failure at each location (i.e., if a bank eroded or collapsed after stabilization; calculated as the percentage of Monte Carlo simulations with failure). Mean restoration failure rates were highest for the baseline and random stormwater scenario and were lowest for the coordinated stormwater simulation (Table 1). Restoration was more likely to fail if it was implemented on reaches that were subject to high erosion rates (e.g., in the middle of the watershed). When coupled with effective stormwater controls, however, these reaches were less erosion prone and therefore had lower rates of failure (Fig. 6).

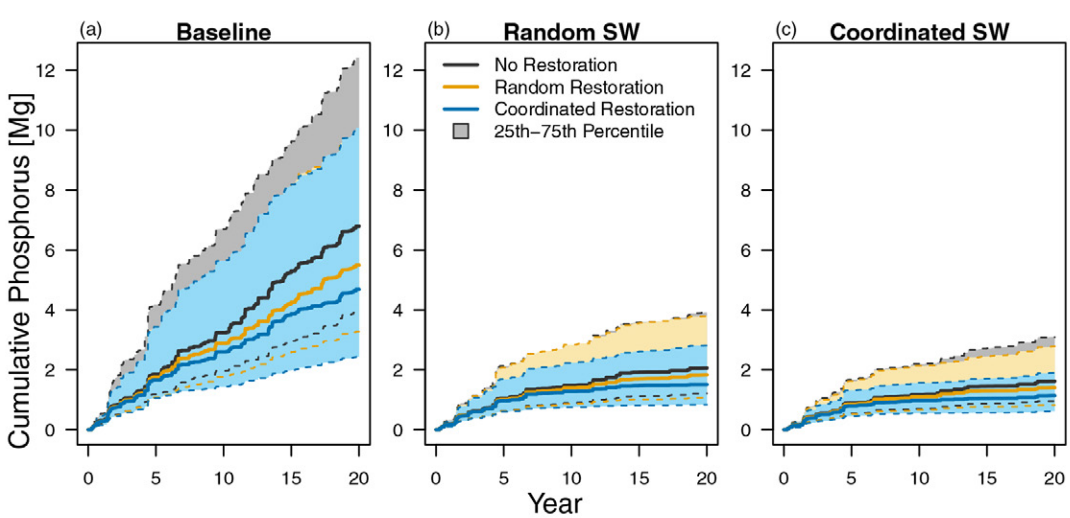

Fig. 2. Cumulative watershed phosphorus loading from channel erosion for each of the three stormwater (SW) scenarios, with uncertainty. Line colors correspond to different stream restoration scenarios.

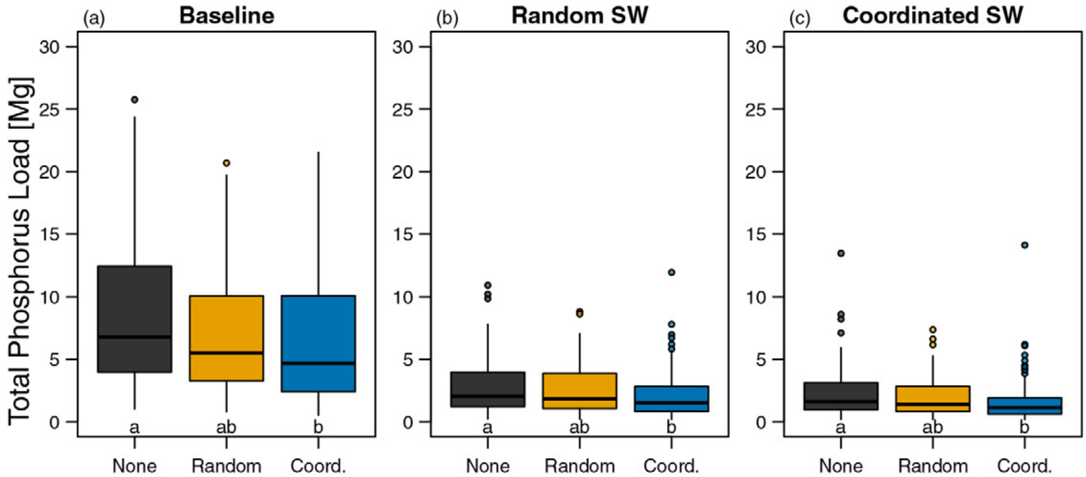

Fig. 3. Boxplots show distributions of cumulative phosphorus load from channel erosion for all stormwater (SW) scenarios. Boxplots with different letters (within each subplot) are significantly different at $\alpha = 0.05$ (Dunn's test with Bonferroni correction). Note: *y* axis scale has been reduced to improve visibility, eliminating some outliers. Coord., coordinated.

Discussion

Our modeling results suggest that watershed-scale implementation of stormwater controls that reduce runoff volume across a spectrum of storm sizes is a more effective approach for reducing channel erosion than stream restoration. Pollutant loading reductions with just stormwater controls were large (~70%), and adding restoration to these scenarios resulted in much smaller water quality gains (~3–8%). Others have noted that addressing the causes of urban stream degradation (i.e., altered hydrology) will likely be more effective for improving stream health than in-channel restoration alone (Walsh et al., 2005a; Bernhardt and Palmer, 2007; Vietz et al., 2016; Anim et al., 2019). Our results suggest a similar conclusion. Although stream restoration in the baseline stormwater scenario did reduce pollutant loading by 20 to 30%, it failed to reduce the rate of loading over time, since the channel remained unstable over the 20-yr modeled period (Fig. 2A, consistently increasing cumulative phosphorus loading). Stormwater control scenarios, on the other hand, led to eventual channel stabilization, even without any stream restoration (Fig. 2B–2C, flattening of cumulative phosphorus loading). This suggests that controlling stormwater runoff allows the channel to restabilize and prevents significant long-term erosion and pollutant loading. The reduction in loading rates over time was also a function of the phased implementation of stormwater controls and stream restoration. Aggressive early implementation likely would have resulted in even less total pollutant loading by avoiding significant erosion early on. Much like investing early leads to greater returns, early implementation of stormwater controls and restoration can result in greater water quality and channel stability benefits.

The two scenarios with stormwater controls were successful in reducing channel erosion and pollutant loading because they managed the entire EURV resulting from urban development, reducing runoff volume in addition to reducing peak flows. These scenarios had ~20% less total runoff over the model period compared with the baseline condition. Although this seems like a large reduction, reducing runoff volume by 30 to 65% was necessary to restore pre-development hydraulic conditions in urban streams in Australia (Anim et al., 2019). A major symptom of urbanization is increased runoff volume, and reducing this volume is essential for controlling channel erosion (McCuen, 1979; Rohrer and Roesner, 2006; Pomeroy et al., 2008). Our approach for reducing runoff volume was aggressive implementation of infiltration-promoting stormwater practices; however, rainwater harvesting may also be an important strategy, especially where land availability is a limiting factor (Burns et al., 2012; Askarizadeh et al., 2015; Anim et al., 2019).

Although reducing runoff volume is likely the most important stormwater goal, reducing the magnitude and duration of

Table 1. Total cumulative sediment and phosphorus loading from channel erosion for all model scenarios, including the percentage reduction in pollutant loading from the baseline stormwater, no restoration scenario. The final column shows the mean probability of failure for restored reaches for scenarios with stream restoration.

Stormwater	Restoration	Total sediment load	Total phosphorus load	Reduction from baseline	Mean restoration failure probability
		Mg		%	
Baseline stormwater	No restoration	24,129	6.8	0	–
	Random restoration	19,436	5.5	19.0	18
	Coordinated restoration	17,766	4.7	31.0	35
Random stormwater	No restoration	7,013	2.1	69.7	–
	Random restoration	6,220	1.8	73.0	11
	Coordinated restoration	5,102	1.5	77.8	22
Coordinated stormwater	No restoration	5,525	1.6	76.2	–
	Random restoration	4,624	1.4	79.3	10
	Coordinated restoration	3,599	1.1	83.2	5

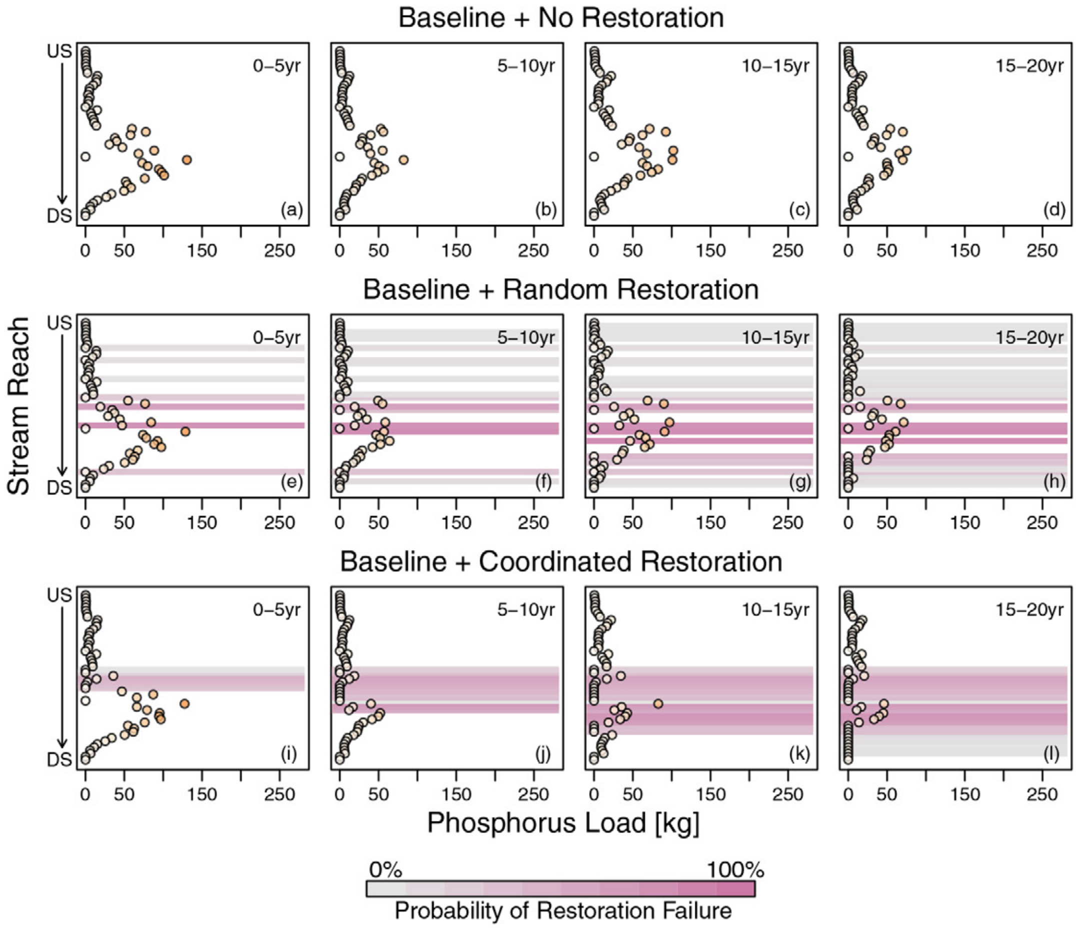

Fig. 4. Phosphorus loading from channel erosion by reach (median of Monte Carlo simulations) over the course of the simulation for different restoration scenarios with the baseline stormwater scenario. Shading indicates the probability of restoration failure for each restored reach. US, upstream; DS, downstream.

peak flows also helps minimize channel erosion. The random and coordinated stormwater scenarios had very similar total runoff volumes (<0.5% difference), but the coordinated scenario had 80 fewer hours above 5 $m^3 s^{-1}$ (an approximate bank erosion threshold for Big Dry Creek). This is a relatively small amount of time over a 20-yr period, but most channel erosion occurs episodically during high-flow events. By beginning to control runoff at the upstream end of the basin and working downstream, the coordinated scenario was able to better reduce both total runoff volume and peak flows, resulting in less channel erosion and pollutant loading than random stormwater implementation. It is possible, however, that other "random" implementation scenarios could be more or less effective in managing runoff. There is a body of work that demonstrates that stormwater controls need to be designed through a watershed-scale, rather than only a site-specific, approach (McCuen, 1974). Otherwise, uncoordinated stormwater controls will not effectively control flows at the watershed outlet and may actually exacerbate problems—for example, by delaying runoff but then releasing flows at the same time, "syncing" peaks from different subbasins and increasing total flow rates (Emerson et al., 2005).

For our modeling, differences between the coordinated and random stormwater scenarios were relatively small (Table 1). One possible explanation is that our simulations were for a relatively small watershed and we applied SCMs very aggressively (fully manage excess urban runoff). Applying these approaches to a larger watershed (with more subbasins) at a less aggressive rate may result in greater differences between random and coordinated stormwater implementation and is an important area for future research. Still, uncertainty in our results is high (Fig. 2 and 3), suggesting that there is a high degree of uncertainty in the effectiveness of stormwater controls and stream restoration projects for increasing channel stability. Analyses that omit this uncertainty could find differences between practices that in reality are not statistically significant, leading to incorrect conclusions about the varying efficacy of these approaches. Additionally, uncertainty was highest for the baseline stormwater scenarios (Fig. 2a and 3a), likely because higher rates of channel erosion and pollutant loading were predicted. The greater the modeled channel change, the larger the associated uncertainty.

Although modeling showed significantly greater reductions in channel erosion and pollutant loading from stormwater controls compared with restoration, this is not to say that channel restoration provides no benefits. We still saw some reduction in pollutant loading, especially in the coordinated restoration scenarios. Channel restoration projects can also have additional benefits that we did not examine here, including improved habitat, protection of critical infrastructure, and improved aesthetics (Nagle, 2007; Buchanan et al., 2010; Cockerill and Anderson, 2014; Palmer et al., 2014). Weighing the multiple benefits of channel restoration is important when considering its cost effectiveness and suitability. Furthermore, the goal is not to

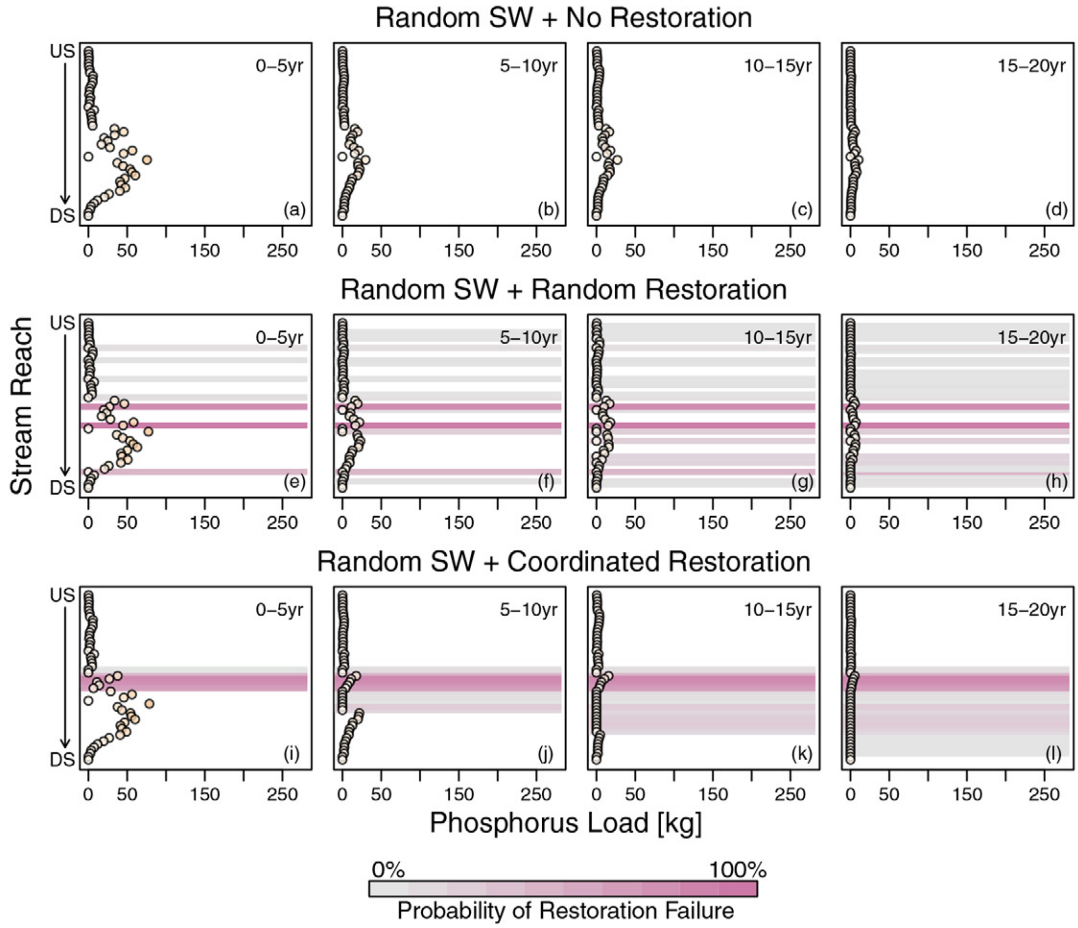

Fig. 5. Phosphorus loading from channel erosion by reach (median of Monte Carlo simulations) over the course of the simulation for different restoration scenarios with the random stormwater (SW) scenario. Shading indicates the probability of restoration failure for each restored reach. US, upstream; DS, downstream.

choose SCMs or restoration, but rather to find the best mix of practices to achieve multiple benefits in urbanizing watersheds. Our results just suggest that effectively managing stream erosion requires effective control of stormwater runoff volumes (addressing the cause), rather than only stabilizing the channels (addressing the symptom).

Spatial variability in channel erosion is important for understanding the impacts of both stormwater controls and stream restoration. The most erosion-prone reaches of Big Dry Creek were located in the lower half of the model domain (Fig. 4–6), primarily because of the large number of stormwater outfalls in this area, which resulted in sharp increases in discharge. Installing stormwater controls in the basins draining to these outfalls helped attenuate these discharge peaks. Additionally, the coordinated restoration scenario was more successful than random implementation because high-loading reaches were specifically targeted for remediation, and restored reaches were connected instead of left as isolated pockets between eroding stream sections. This underscores the need to take a watershed-scale approach to restoration and target projects where they will have the greatest benefit (Roni and Beechie, 2013). In reality, most stream reaches are selected for restoration based on land availability and ease of access. This is a significant limitation of restoration, especially in urban areas where much of the riparian land is privately owned. In Big Dry Creek, and in some other watersheds, much of the riparian land is owned by municipalities and is used as parkland. This has substantial benefits for flood risk reduction but also facilitates larger-scale, coordinated stream restoration.

A number of restored reaches "failed" in the different scenarios (Table 1, Fig. 4–6), meaning the increased critical shear stress and soil cohesion from restoration was insufficient to protect the banks from erosion and/or collapse. Average failure rates where highest under the baseline stormwater scenario (18–35%) and were lowest under the coordinated stormwater scenario (5–10%). The coordinated restoration scenario had higher failure probabilities than random restoration, likely because reaches that were more susceptible to erosion were specifically targeted for restoration. The exception to this was the coordinated stormwater scenario, where coordinated restoration had the lowest overall mean failure probability (5%). This suggests that both coordinated stormwater and restoration are required to successfully protect the channel from erosion. Project failure or blowout is not an uncommon outcome of urban stream restoration projects, which are subject to large and erosive peak flows that are often not adequately mitigated with stormwater controls (Buchanan et al., 2010; Miller and Kochel, 2010, 2013). Urban stream restoration projects fail for a number of reasons (Smith and Prestegaard, 2005; Miller and Kochel, 2013). In our model, restoration failed if the critical shear stress of the restored bank was exceeded, or if the bank collapsed due to mass failure. When structure-based restoration projects fail, the mobilized structure

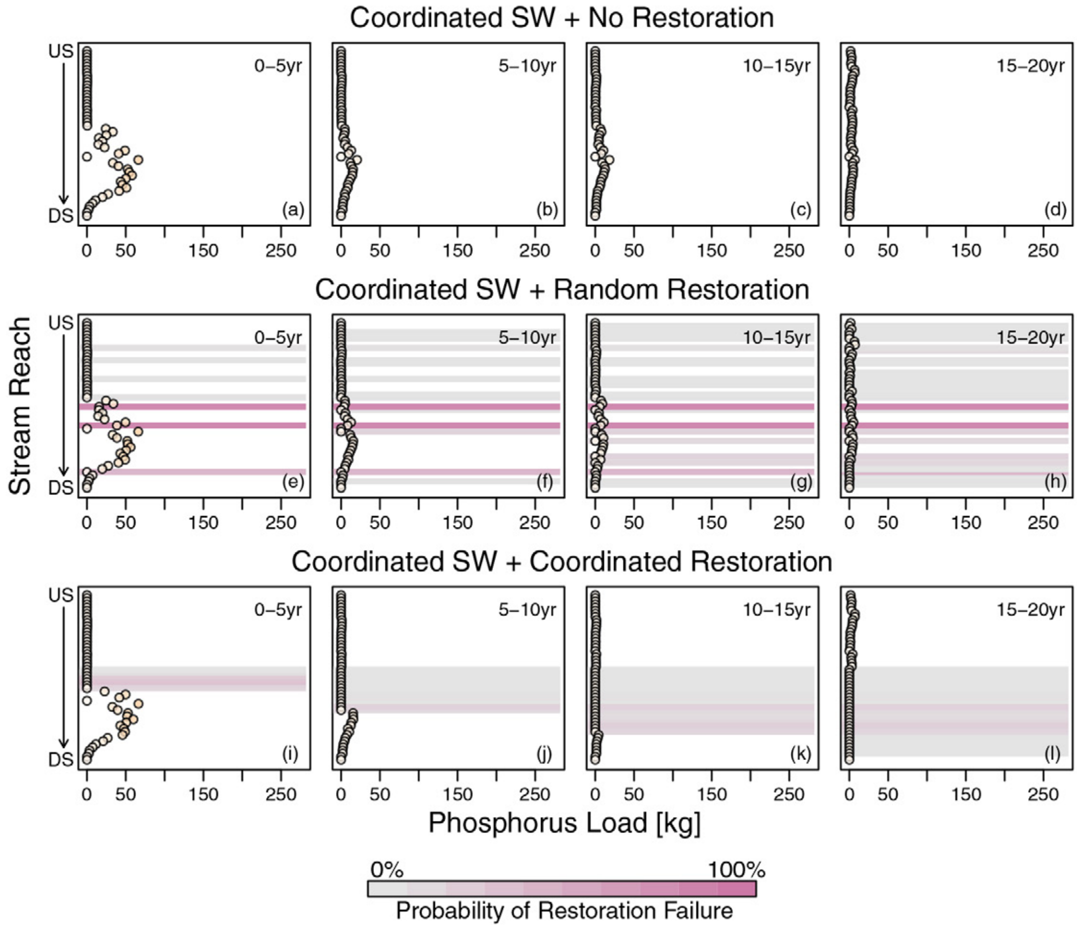

Fig. 6. Phosphorus loading from channel erosion by reach (median of Monte Carlo simulations) over the course of the simulation for different restoration scenarios with the coordinated stormwater (SW) scenario. Shading indicates the probability of restoration failure for each restored reach. US, upstream; DS, downstream.

can actually accelerate channel erosion by deflecting flow toward an erodible bank or cause channel avulsion (Buchanan et al., 2010). We did not include these failure mechanisms and therefore our modeling may actually be underpredicting the negative side effects of restoration failure.

The results of this work add to the growing evidence that (i) improperly designed stormwater controls can be ineffective at protecting stream channels (McCuen, 1979; Emerson et al., 2005) and (ii) more targeted design of these features can improve their ability to reduce channel erosion, leading to significant water quality benefits (Bledsoe, 2002; Rohrer and Roesner, 2006; Pomeroy et al., 2008; Elliott et al., 2010; Tillinghast et al., 2012). Furthermore, we build on this previous work by showing that stream restoration can complement effective stormwater treatment to reduce erosion and pollutant loading, but that these approaches should be coordinated to achieve the best results. Given these findings, we propose the following recommendations for putting this approach into practice:

1. Determine erosion thresholds of channels. This includes determining whether the bed or banks are most susceptible to erosion (Bledsoe, 2001) and can range from simple estimates of a discharge threshold (Tillinghast et al., 2011; Hawley and Vietz, 2016) to detailed hydraulic modeling. Previous work on Big Dry Creek demonstrated that the channel was more susceptible to widening than incision (Lammers and Bledsoe, 2019), and we identified an approximate erosion threshold of 5 $m^3 s^{-1}$ based on the critical shear stress of the bank soil.

2. Design restoration projects based on the dominant mode of adjustment (e.g., widening vs. initially incising), recognizing that the type of channel erosion may change in the future. In this case study, we targeted restoration to stabilize channel banks.

3. Design stormwater controls to reduce runoff volume and the frequency *and* duration of flows above these erosion thresholds, while also accounting for other design objectives such as flood control and water quality (McCuen and Moglen, 1988; Hawley and Vietz, 2016). In more erodible channels, this will require targeting smaller, more frequent flows (i.e., <2-yr event) (Nehrke and Roesner, 2004; Emerson et al., 2005; Tillinghast et al., 2011). In this paper, we designed stormwater controls to treat the EURV, reducing runoff volume across all storm sizes.

4. Begin restoration upstream and move downstream, in conjunction with stormwater controls. Restore continuous sections of stream versus disparate patches. In this study, our coordinated restoration performed better than random in part because continuous sections of channel were restored. Our coordination of SCMs and restoration was relatively simple.

5. Be prepared for rapid intervention if restoration fails early on. Restoration projects should be implemented only where there is a high likelihood of success, even under an evolving hydrologic and sediment regime; however, these are stochastic processes and some failure will likely occur even when projects are carefully planned. In this study, we showed that restoration projects can fail even when coordinated with stormwater controls. The rigidity of the design (from complete armoring to allowing some channel mobility) will vary depending on local constraints and affect project resiliency (Kondolf, 2011). Many restoration projects lead to almost complete removal of vegetation at the project site, which reduces flow resistance and makes the channel susceptible to erosion (Buchanan et al., 2010; Hawley, 2018), especially soon after construction. Lighter footprint approaches that keep vegetation in place can reduce this risk.

6. Monitor and adapt as needed. Even well-designed and coordinated projects can fail (as we saw with our coordinated stormwater and coordinated restoration scenario). Continuous monitoring and adaption is therefore required for these complex systems.

Other studies have examined links between stormwater controls and channel stability (Tillinghast et al., 2012; Anim et al., 2019), but this is the first attempt to use physically based modeling to explore links between stormwater controls, stream restoration, and channel stability and their effects on sediment and phosphorus loading. Although this is an important first step, additional research is needed to expand on this approach. For example, modeling a larger, more heterogeneous watershed could reveal more complicated responses and interactions between different stormwater implementation scenarios. Furthermore, our stormwater scenarios both included infiltration practices and therefore led to significant runoff volume reduction. It is important to compare the efficacy of these infiltration based approaches with a more traditional "peak shaving" approach that reduces peak flows but does not reduce runoff volumes. This could add to growing evidence that stormwater controls that fail to reduce the volume of runoff are ineffective at protecting stream channels (McCuen, 1979; Pomeroy et al., 2008; Tillinghast et al., 2012). Additionally, a comparison between stormwater controls that are designed to meet a more traditional water quality control standard and a full-spectrum design (i.e., capture the EURV) would evaluate the potential advantages of the less common full-spectrum approach.

Incorporating relative costs of stormwater versus restoration could also help determine the most cost-effective mix of practices that achieves project goals (Niezgoda and Johnson, 2012). Finally, our study only examined one type of channel restoration (bank grading and stabilization). Other restoration practices may effectively reduce channel erosion, either on their own or in conjunction with bank stabilization. Floodplain restoration can reduce the magnitude of in-channel flows and associated erosive power, instead allowing energy to dissipate on the floodplain. Grade control structures increase vertical stability in channels, which can prevent bank undercutting and collapse. Exploring interactions between these additional restoration practices and stormwater controls would improve understanding of the most effective approach for limiting channel erosion in urbanized watersheds across a wide geomorphic gradient.

Supplemental Material

The supplemental material includes additional details on inputs for the REM and a table of imperviousness assumed for different land use classifications.

Conflict of Interest

The authors declare no conflict of interest.

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References

Anim, D.O., T.D. Fletcher, G.B. Pasternack, G.J. Vietz, H.P. Duncan, and M.J. Burns. 2019. Can catchment-scale urban stormwater management measures benefit the stream hydraulic environment? J. Environ. Manage. 233:1–11. doi:10.1016/j.jenvman.2018.12.023

Anim, D.O., T.D. Fletcher, G.J. Vietz, G.B. Pasternack, and M.J. Burns. 2018. Restoring in-stream habitat in urban catchments: Modify flow or the channel? Ecohydrology 12:e2050. doi:10.1002/eco.2050

Askarizadeh, A., M.A. Rippy, T.D. Fletcher, D.L. Feldman, J. Peng, P. Bowler, et al. 2015. From rain tanks to catchments: Use of low-impact development to address hydrologic symptoms of the urban stream syndrome. Environ. Sci. Technol. 49:11264–11280. doi:10.1021/acs.est.5b01635

Bernhardt, E.S., and M.A. Palmer. 2007. Restoring streams in an urbanizing world. Freshw. Biol. 52:738–751. doi:10.1111/j.1365-2427.2006.01718.x

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, et al. 2005. Synthesizing U.S. river restoration efforts. Science 308:636–637. doi:10.1126/science.1109769

Bhaskar, A.S., L. Beesley, M.J. Burns, T.D. Fletcher, P. Hamel, C.E. Oldham, and A.H. Roy. 2016. Will it rise or will it fall? Managing the complex effects of urbanization on base flow. Freshw. Sci. 35:293–310. doi:10.1086/685084

Bledsoe, B.P. 2001. Relationships of stream responses to hydrologic changes. In: B.R. Urbonas, editor, Linking stormwater BMP designs and performance to receiving water impact mitigation. Am. Soc. Civil Eng., Reston, VA. p. 127–144. doi:10.1061/40602%28263%2910

Bledsoe, B.P. 2002. Stream erosion potential and stormwater management strategies. J. Water Resour. Plan. Manage. 128:451–455. doi:10.1061/(ASCE)0733-9496(2002)128:6(451)

Bledsoe, B.P., E.D. Stein, R.J. Hawley, and D. Booth. 2012. Framework and tool for rapid assessment of stream susceptibility to hydromodification. J. Am. Water Resour. Assoc. 48:788–808. doi:10.1111/j.1752-1688.2012.00653.x

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. Water Resour. Bull. 26:407–417. doi:10.1111/j.1752-1688.1990.tb01380.x

Buchanan, B.P., W.T. Walter, G.N. Nagle, and R.L. Schneider. 2010. Monitoring and assessment of a river restoration project in central New York. River Res. Appl. 28:216–233. doi:10.1002/rra.1453

Burns, M.J., T.D. Fletcher, C.J. Walsh, A.R. Ladson, and B.E. Hatt. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landsc. Urban Plan. 105:230–240. doi:10.1016/j.landurbplan.2011.12.012

Clary, J. 2017. Big Dry Creek annual water quality summary for 2016. Big Dry Creek Watershed Assoc., Broomfield, CO.

Cockerill, K., and W.P. Anderson. 2014. Creating false images: Stream restoration in an urban setting. J. Am. Water Resour. Assoc. 50:468–482. doi:10.1111/jawr.12131

Eckhardt, K. 2005. How to construct recursive digital filters for baseflow separation. Hydrol. Processes 19:507–515. doi:10.1002/hyp.5675

Elliott, A.H., R.H. Spigel, I.G. Jowett, S.U. Shankar, and R.P. Ibbitt. 2010. Model application to assess effects of urbanisation and distributed flow controls on erosion potential and baseflow hydraulic habitat. Urban Water J. 7:91–107. doi:10.1080/15730620903447605

Emerson, C.H., C. Welty, and R.G. Traver. 2005. Watershed-scale evaluation of a system of storm water detention basins. J. Hydrol. Eng. 10:237–242. doi:10.1061/(ASCE)1084-0699(2005)10:3(237)

Ernst, A.G., D.R. Warren, and B.P. Baldigo. 2012. Natural-channel-design restorations that changed geomorphology have little effect on macroinvertebrate communities in headwater streams. Restor. Ecol. 20:532–540. doi:10.1111/j.1526-100X.2011.00790.x

Fox, G.A., R.A. Purvis, and C.J. Penn. 2016. Streambanks: A net source of sediment and phosphorus to streams and rivers. J. Environ. Manage. 181:602–614. doi:10.1016/j.jenvman.2016.06.071

Hawley, R.J. 2018. Making stream restoration more sustainable: A geomorphically, ecologically, and socioeconomically principled approach to bridge the practice with the science. Bioscience 68:517–528. doi:10.1093/biosci/biy048

Hawley, R.J., and G. Vietz. 2016. Addressing the urban stream disturbance regime. Freshw. Sci. 35:278–292. doi:10.1086/684647

Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, et al. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States- Representing a decade of land cover change information. Photogramm. Eng. Remote Sensing 81:345–354.

Hubbart, J.A., and C. Zell. 2013. Considering streamflow trend analyses uncertainty in urbanizing watersheds: A baseflow case study in the central United States. Earth Interact. 17(5). doi:10.1175/2012EI000481.1

Kondolf, G.M. 2011. Setting goals in river restoration: When and where can the river "heal itself"? In: A. Simon, et al., editors, Stream restoration in dynamic fluvial systems: Scientific approaches, analyses, and tools. Am. Geophys. Union, Washington, DC. p. 29–43. doi:10.1029/2010GM001020

Lammers, R.W., and B.P. Bledsoe. 2018. A network scale, intermediate complexity model for simulating channel evolution over years to decades. J. Hydrol. 566:886–900. doi:10.1016/j.jhydrol.2018.09.036

Lammers, R.W., and B.P. Bledsoe. 2019. Quantifying pollutant loading from channel sources: Watershed-scale application of the River Erosion Model. J. Environ. Manage. 234:104–114. doi:10.1016/j.jenvman.2018.12.074

Leopold, L. 1968. Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. Circ. 554. USGS, Reston, VA.

Lim, K.J., B.A. Engel, Z. Tang, and J. Choi. 2005. Automated web GIS based hydrograph analysis tool, WHAT. J. Am. Water Resour. Assoc. 41:1407–1416. doi:10.1111/j.1752-1688.2005.tb03808.x

McCuen, R.H. 1974. A regional approach to urban storm water detention. Geophys. Res. Lett. 1:321–322. doi:10.1029/GL001i007p00321

McCuen, R.H. 1979. Downstream effects of stormwater management basins. J. Hydraul. Div. 105:1343–1356.

McCuen, R.H., and G.E. Moglen. 1988. Multicriterion stormwater management methods. J. Water Resour. Plan. Manage. 114:414–431. doi:10.1061/(ASCE)0733-9496(1988)114:4(414)

Miller, J.R., and R.C. Kochel. 2010. Assessment of channel dynamics, in-stream structures and post-project channel adjustments in North Carolina and its implications to effective stream restoration. Environ. Earth Sci. 59:1681–1692. doi:10.1007/s12665-009-0150-1

Miller, J.R., and R.C. Kochel. 2013. Use and performance of in-stream structures for river restoration: A case study from North Carolina. Environ. Earth Sci. 68:1563–1574. doi:10.1007/s12665-012-1850-5

Nagle, G. 2007. Evaluating "natural channel design" stream projects. Hydrol. Processes 21:2539–2545. doi:10.1002/hyp.6840

Nehrke, S.M., and L.A. Roesner. 2004. Effects of design practice for flood control and best management practices on the flow-frequency curve. J. Water Resour. Plan. Manage. 130:131–139. doi:10.1061/(ASCE)0733-9496(2004)130:2(131)

Niezgoda, S.L., and P.a. Johnson. 2012. Applying risk-benefit analysis to select an appropriate streambank stabilization measure. J. Hydraul. Eng. 138:449–461. doi:10.1061/(ASCE)HY.1943-7900.0000530

NRCS. 2007. Stream restoration design. Natl. Eng. Handb., Part 654 210-VI-NEH. USDA Nat. Resour. Conserv. Serv., Washington, DC.

Palmer, M.A., K.L. Hondula, and B.J. Koch. 2014. Ecological restoration of streams and rivers: Shifting strategies and shifting goals. Annu. Rev. Ecol. Evol. Syst. 45:247–269. doi:10.1146/annurev-ecolsys-120213-091935

Pollen-Bankhead, N., and A. Simon. 2008. Enhanced application of root-reinforcement algorithms for bank-stability modeling. Earth Surf. Processes Landforms 34:471–480. doi:10.1002/esp.1690

Polvi, L.E., E.E. Wohl, and D.M. Merritt. 2014. Modeling the functional influence of vegetation type on streambank cohesion. Earth Surf. Processes Landforms 39:1245–1258. doi:10.1002/esp.3577

Pomeroy, C.a., N.A. Postel, P.a. O'Neill, and L.A. Roesner. 2008. Development of storm-water management design criteria to maintain geomorphic stability in Kansas City metropolitan area streams. J. Irrig. Drain. Eng. 134:562–566. doi:10.1061/(ASCE)0733-9437(2008)134:5(562)

R Core Team. 2018. R: A language and environment for statistical computing. R Found. Stat. Comput., Vienna.

Rohrer, C.A., and L.A. Roesner. 2006. Matching the critical portion of the flow duration curve to minimise changes in modelled excess shear. Water Sci. Technol. 54:347–354. doi:10.2166/wst.2006.590

Roni, P., and T. Beechie. 2013. Stream and watershed restoration: A guide to restoring riverine processes and habitats. John Wiley & Sons, Hoboken, NJ.

Rossman, L.A. 2015. Storm Water Management Model user's manual version 5.1. USEPA, Cincinnati, OH.

Selvakumar, A., T.P. O'Connor, and S.D. Struck. 2010. Role of stream restoration on improving benthic macroinvertebrates and in-stream water quality in an urban watershed: Case study. J. Environ. Eng. 136:127–139. doi:10.1061/(ASCE)EE.1943-7870.0000116

Simon, A., and A.J. Collison. 2001. Pore-water pressure effects on the detachment of cohesive streambeds: Seepage forces and matric suction. Earth Surf. Processes Landforms 26:1421–1442. doi:10.1002/esp.287

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology 35:193–217. doi:10.1016/S0169-555X(00)00036-2

Smith, S.M., and K.L. Prestegaard. 2005. Hydraulic performance of a morphology-based stream channel design. Water Resour. Res. 41:1–17. doi:10.1029/2004WR003926

Tillinghast, E.D., W.F. Hunt, and G.D. Jennings. 2011. Stormwater control measure (SCM) design standards to limit stream erosion for Piedmont North Carolina. J. Hydrol. 411:185–196. doi:10.1016/j.jhydrol.2011.09.027

Tillinghast, E.D., W.F. Hunt, G.D. Jennings, and P. D'Arconte. 2012. Increasing stream geomorphic stability using storm water control measures in a densely urbanized watershed. J. Hydrol. Eng. 17:1381–1388. doi:10.1061/(ASCE)HE.1943-5584.0000577

UDFCD. 2016. Urban storm drainage criteria manual. Vol. 2. Urban Drain. Flood Control District, Denver, CO.

Vietz, G.J., I.D. Rutherfurd, T.D. Fletcher, and C.J. Walsh. 2016. Thinking outside the channel: Challenges and opportunities for protection and restoration of stream morphology in urbanizing catchments. Landsc. Urban Plan. 145:34–44. doi:10.1016/j.landurbplan.2015.09.004

Walsh, C.J., T.D. Fletcher, and A.R. Ladson. 2005a. Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream. J. North Am. Benthol. Soc. 24:690–705. doi:10.1899/04-020.1

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan II. 2005b. The urban stream syndrome: Current knowledge and the search for a cure. Freshwater Sci. 24:706–723. doi:10.1899/04-028.1

Wright Water Engineers. 2010. Big Dry Creek major drainageway plan digital flood hazard area delineation. Wright Water Eng., Denver, CO.

Supplemental Material for "Integrating stormwater management and stream restoration strategies for greater water quality benefits"

Data Collection Methods for River Erosion Model Inputs

Model inputs for REM are shown in Table S1. For inputs varied in the Monte Carlo simulations, the distribution of values used are also shown. These model inputs are from Lammers & Bledsoe (2019), and readers are directed to that paper for more details. However, we do provide a short description of how bank cohesion and critical shear stress were quantified, since these are especially important inputs in our modeling.

We used measured bank heights and angles for stable and unstable banks in Big Dry Creek to fit a logistic regression equation to predict the probability of bank failure (p):

$$\ln \frac{p}{1-p} = \beta_o + \beta_\alpha \ln \alpha + \beta_H \ln H$$

Where α is bank angle, H is bank height, and β_o, β_α, and β_H are fitted model coefficients. This logistic regression model was solved for a bank failure probability of 50% (p = 0.5) and used in conjunction with the Culmann equation for geotechnical slab failure to estimate the effective cohesion of the bank material. For this analysis, we assumed that soil unit weight varied between 16.9 and 19.2 kN/m^3, and friction angle varied between 11.4 and 32.3 degrees (Simon et al., 2011).

We estimated critical shear stress of bank material using erosion rates estimated from aerial images (from 1993 and 2014), as well as stream gage data over this time period (USGS gage 06720820). This discharge data was used with an estimate of channel slope and width to calculate specific stream power, which was then converted to a bank shear stress value using the same empirical equation that is used in REM (Lammers & Bledsoe, 2018). A critical shear stress value was calculated for the streambanks that provided the best match between observed and predicted erosion over the analyzed time period.

Table S1. Model inputs for the River Erosion Model. Inputs with information under the "MC Values" column were varied in the uncertainty analysis. See Lammers & Bledsoe (2019) for details.

Variable	Value	MC Values	Source
Bed profile	--	--	DEM
Bank geometry	0.5 - 1.9 m; 45 - 80°	±50%[1]	Measured
Width [m]	5.3-6.8 m		DEM
Discharge	--	--	SWMM modeling
Sediment supply	50% of transport capacity	--	Lammers & Bledsoe (2019)
Bank τ_c [Pa]	7.2	±50%[1]	Calibrated
Restored bank τ_c [Pa]	23.9 - 47.9	--	NRCS (2007)
Bank cohesion [kPa]	1.4	Normal (mean = 1.4; sd = 0.4)	Calculated from bank geometry
Restored bank cohesion [kPa]	4.4	--	Polvi et al. (2014)
Bank friction angle, ϕ [deg]	22	±50%[1]	Typical values (Simon et al., 2011)

Bank soil weight [kN/m^3]	18	±50%[1]	Typical values (Simon et al., 2011)
Bank P [mg/kg]	310	Normal (mean = 310; sd = 100)	Measured
Bank bedload prop	38-64%	±50%[1]	% sand from sampled banks
Cohesive bed	Three grade control structures	--	Field observations
Grain size distribution	D_{50} = 2 mm; σ_g = 1.5	50%	Assumed
Floodplain geometry	Width: 50 m; slope: 1°	±50%[1]	Assumed
Manning n	Chnl: 0.035; fp: 0.06	±50%[1]	Assumed
Radius of curvature [m]	35	±50%[1]	Aerial imagery
Sinuosity	1.52 - 1.87	±50%[1]	Aerial imagery

[1]Uniform distribution

[2]Proportion of the eroded bank that is bed material load (sand and coarser). The rest is assumed to be washload.

Table S2. Summary of percent imperviousness assigned to different land use categories for the SWMM model (from Wright Water Engineers, 2010).

Land Use Category	% Impervious
Undeveloped Areas: Greenbelts, agriculture	2
Parks, Cemeteries	5
Railroad Yard Areas/Mining Areas/Service Yard	15
Residential: One-acre lot or larger/Rural Estate	20
Residential: Single Family Low (0.5 to 1.0 acres)	35
Residential: Single Family Medium (0.25 to 0.5 acres)	50
Schools/Community Center/Church	50
Residential: Multi-Unit (Detached)	60
Residential: Single Family High (< 0.25 acres)	65
Residential: Multi-Unit (Attached)	75
Institutional	75
Residential: Apartments/Condominiums	80
Commercial/Broomfield Comprehensive Plan (Future Only)	80
Industrial: Light Areas	80
Industrial: Unspecified	85
Business: Neighborhood Areas/Mixed Use/Employment/ Business Park	85
Commercial/Thornton Regional Commercial	85
Business: Commercial Areas	95

References

Lammers, R. W., & Bledsoe, B. P. (2018). A network scale, intermediate complexity model for simulating channel evolution over years to decades. *Journal of Hydrology*, *566*, 886–900. https://doi.org/10.1016/j.jhydrol.2018.09.036

Lammers, R. W., & Bledsoe, B. P. (2019). Quantifying pollutant loading from channel sources: Watershed-scale application of the River Erosion Model. *Journal of Environmental Management*, *234*, 104–114. https://doi.org/10.1016/j.jenvman.2018.12.074

NRCS. (2007). *Stream Restoration Design*. National Engineering Handbook, Part 654 210-VI-NEH.

Polvi, L. E., Wohl, E. E., & Merritt, D. M. (2014). Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, *39*(9), 1245–1258. https://doi.org/10.1002/esp.3577

Simon, A., Pollen-Bankhead, N., & Thomas, R. E. (2011). Development and application of a deterministic bank stability and toe erosion model for stream restoration. In A. Simon, S. Bennett, & J. Castro (Eds.), *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools* (pp. 453–474). Washington, D.C.: American Geophysical Union.

Wright Water Engineers. (2010). *Big Dry Creek major drainageway plan digital flood hazard area delineation*. Denver, CO.