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DETENTION OUTLET RETROFIT IMPROVES THE FUNCTIONALITY OF EXISTING DETENTION BASINS BY REDUCING EROSIVE FLOWS IN RECEIVING CHANNELS

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Abstract

By discharging excess stormwater at rates that more frequently exceed the critical flow for stream erosion, conventional detention basins often contribute to increased channel instability in urban and suburban systems that can be detrimental to aquatic habitat and water quality, as well as adjacent property and infrastructure. However, these ubiquitous assets, valued at approximately \$600,000 per km^2 in a representative suburban watershed, are ideal candidates to aid in reversing

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such cycles of channel degradation because improving their functionality would not necessarily require property acquisition or heavy construction. The objective of this research was to develop a simple, cost-effective device that could be installed in detention basin outlets to reduce the erosive power of the relatively frequent storm events (~ < two-year recurrence) and provide a passive bypass to maintain flood control performance during infrequent storms (such as the 100-year recurrence). Results from a pilot installation show that the Detain H_2O device reduced the cumulative sediment transport capacity of the preretrofit condition by greater than 40%, and contributed to reduced flashiness and prolonged baseflows in receiving streams. When scaling the strategy across a watershed, these results suggest that potential gains in water quality and stream channel stability could be achieved at costs that are orders of magnitude less than comparable benefits from newly constructed stormwater control measures.

Keywords

best management practices; detention basin retrofits; hydromodification; stormwater management; stream stability/erosion; urbanization

INTRODUCTION

Detention basins are ubiquitous stormwater management facilities in the United States (U.S.), particularly in suburban areas that were developed since the 1980s. For example, in one approximately 93 km^2 suburban watershed of Northern Kentucky with an average impervious cover of about 25%, there are an estimated 535 detention basins or an average of 1 detention basin per 18 ha. Using average values for basin size and present-day construction costs (Hawley *et al.,* 2012b), the order-of-magnitude value of these assets is scaled to approximately $60 M, or an average of $600,000 in stormwater management assets per square kilometer within the watershed.

Until as recently as the last decade, detention basins were almost exclusively designed to meet flood protection criteria that typically involved managing stormwater runoff from new developments such that peak discharges did not exceed those of the predeveloped conditions for specific flood frequency recurrence intervals such as the 2-, 10-, 25-, 50-, and 100-year design storms (Roy *et al.,* 2008). Because conventional development practices invariably create greater runoff volumes than predeveloped watersheds, the so-called “peak matching” strategy nearly universally results in prolonged durations of flows with relatively high magnitudes (Bledsoe, 2002; Figure 1). In many streams this results in increased durations of flows that exceed the critical flow (Q_{critical}) for bed particle mobilization because Q_{critical} can be considerably less than the two-year peak flow, particularly in streams with bed material composed of small cobbles, gravels, or sand (Rohrer and Roesner, 2006; Pomeroy *et al.,* 2008; Hawley and Vietz, 2016). Indeed, conventional peak-matching designs can result in longer durations of flows that have the power to erode the streambed in such gravel- and sand-dominated streams (Bledsoe, 2002; Figure 1). Furthermore, because the two-year flow tends to be the smallest discharge that conventional detention basins are optimized to control, these stormwater facilities tend to have little attenuating effects on more frequent precipitation events, with one study suggesting that up to 97% of the events in a typical year have essentially no attenuation (Emerson *et al.,* 2003). In consequence, lesser storms such as the 3-mo or 6-mo event that may not have caused stream erosion under predeveloped conditions may be amplified and discharged at rates that exceed Q_{critical} under postdeveloped conditions. The cumulative effect is that conventional stormwater management policies tend to increase the frequency, duration, and/or magnitude of flows that exceed the threshold for stream channel erosion in developed watersheds (MacRae, 1997; Konrad and Booth, 2002; Rohrer and Roesner, 2006; Pomeroy *et al.,* 2008). These policies have also failed to preserve other elements of the natural flow regime that can be important for stream integrity (Poff *et al.,* 1997), with, for example, urban and suburban streams almost universally exhibiting flashier flow regimes than rural streams from the same hydroclimatic setting (Poff *et al.,* 2006; Eng *et al.,* 2013).

The widespread application of the peak-matching management strategy across North America has allowed numerous researchers to point to its ineffectiveness in protecting stream integrity — despite large investments in stormwater infrastructure, the biological, chemical, and physical integrity of streams in urban and suburban watersheds substantially departs from those in undeveloped watersheds (Booth, 2005; Walsh *et al.,* 2005; NRC, 2009). For example, in developed watersheds with widespread incorporation of peak-matching control strategies, urban and suburban streams tend to have enlarged and more unstable channels with actively eroding banks and more homogenous habitat than those in rural watersheds (MacRae, 1997; Hawley *et al.,* 2013a). These impacts have become so ubiquitous that "hydromodification," which among other types of hydrologic modification includes urban-induced flow amplification and associated channel erosion, is listed as the second most common source of impairment in U.S. rivers and streams (EPA, 2009).

These management outcomes are not only inconsistent with the goals of the Clean Water Act but are also counterproductive in terms of infrastructure sustainability and asset management. With roads, power utilities, and water/sewer infrastructure commonly placed adjacent to and across streams, urban-induced channel erosion, downcutting, and widening can necessitate repairs, stabilization efforts, and/or premature replacement/relocation. For example, using costs from Northern Kentucky, Hawley *et al.* (2013b) estimated approximately \$10,000, \$1,000, and \$350 per km^2-yr, in impacts to roads, sewers, and power utilities, respectively, that were attributable to channel erosion.

For these and other reasons, there is a growing consensus that more effective stormwater management is needed (Roy *et al.,* 2008; NRC, 2009). This includes a need for more sustainable strategies that preserve stream integrity downstream of new developments as well as cost-effective strategies that begin to reverse the trajectories of degradation in previously developed watersheds. It follows that systematically retrofitting the ubiquitous, conventionally designed detention basins to minimize the extent of channel erosion in receiving streams would be beneficial to both the built and natural environment. Although a modeling study by Postel *et al.* (2009) concluded that there would be limited improvements to stream hydrology or biotic integrity with 30% of a watershed's detention basins retrofitted, the authors suggested that more significant improvements might occur by retrofitting a greater portion of detention basins. It is also important to note that many of the previous efforts related to detention basin retrofits (Marcoon and Guo, 2004; Guo, 2008;

Postel *et al.,* 2009) did not explicitly incorporate a design strategy to minimize downstream channel erosion.

Our approach recognizes the role of the geomorphic setting in connecting watershed hydrology with the ecologically relevant threshold for benthic disturbance via the critical flow for streambed erosion (Hawley *et al.,* 2016). For example, retrofitting a detention basin that exceeds Q_{critical} approximately two to four times per year under a conventional design to a regime that does not exceed Q_{critical} more frequently than once every two years would be a four- to eightfold decrease in disturbance frequency. A retrofit strategy that restores a more natural disturbance regime may enable the transformation of an impaired aquatic community dominated by fast-lived multivoltine organisms to a more diverse community that included longer-lived species such as uni- or semivoltine organisms (Townsend *et al.*, 1997). It may also provide enough time for vegetation to successfully colonize recently deposited sediment at the toes of otherwise unstable streambanks, increasing the probability of a shift from an erosional state of channel evolution (Stages 2, 3, or 4 of the Schumm *et al.* (1984) Channel Evolution Model [CEM]) to a more recovered state of pseudo- (Stage 4) or even full equilibrium (Stage 5).

Facilitating such changes to the flow regime that is discharged from a conventionally designed detention basin does not necessarily require expensive regrading or additional excavation to make the storage volume larger. Indeed, retrofit strategies that are able to meet ecologically and geomorphically relevant hydrologic design goals within the limits of the existing facility have the potential to be much more cost-effective than those that require additional excavation. For example, even relatively minor earthwork, such as excavating the bottom ~0.9 m of soil and replacing it with amended soil media that promotes infiltration could cost ~$50,000 to $100,000 on a small basin draining ~6.5 ha, whereas simply reconfiguring the outlet control structure in the absence of additional excavation would be more likely to cost ~ $5,000 to $10,000 per basin. Furthermore, considering that these facilities are designed to have stormwater runoff directed to them during nearly every storm, approaches that require earthwork within the detention basin can create additional challenges by denuding existing vegetation ground cover, which not only requires reestablishment after construction but poses risks to water quality in terms of construction site sediment runoff.

The scale of the problem as well as the abundance of conventional detention basins underscore the potential benefits of developing a simple, cost-effective strategy for achieving the retrofit performance goals (*i.e.,* with limited funds for stormwater investments, low cost strategies have the potential to restore much greater stream lengths than higher costing alternatives). We propose a strategy that does not disturb the existing ground cover or require additional excavation, but simply optimizes the existing outlet to take greater advantage of the basin's existing storage capacity. To that end, the goal of this research was to develop a simple device that reduces the cumulative erosive power in the receiving stream by restricting the more frequent storm events (up to the two-year storm) to be released below Q_{critical} and achieving comparable flood control performance of the preretrofit configuration during larger and more infrequent events (5-, 10-, 25-, 50-, and 100-year events). The device should be relatively easy to install, with minimal, if any need for heavy equipment. Due to

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the risks associated with a failure during a large event such as the 100-year storm, the device should also minimize the reliance on moving parts to the extent possible, or have otherwise failsafe controls to ensure adequate performance during flood events. Furthermore, the device should be economical, with the design, materials, and installation on the order of ~ $10,000 per detention basin, with potential opportunities for additional cost savings if using a utility's in-house staff for design and/or installation.

To meet these goals we designed and field tested a prototype of the Detain H_2O retrofit technology (Hawley *et al.,* Patent Pending. Detain H2O – Detention Pond Retrofit Device. U.S. Serial Number 61/ 958,027). The objectives of this article are to present the hydrologic modeling and monitoring results of a prototype installation including comparisons of pre- and postretrofit performance using:

1. Modeled design storms (3 months through 100 years).
2. Monitoring precipitation and outflow data for comparable events to the extent feasible given the nature of a field study.
3. Receiving stream (spur), control (upstream), and downstream stage data from comparable monitoring records.

Methodology

The Detain H_2O device (Hawley *et al.*, Patent Pending. Detain H2O – Detention Pond Retrofit Device. U.S. Serial Number 61/958,027) was designed with the goal to be scalable to different size detention basins and/or Q_{critical} targets, allow for a passive bypass to maintain flood control performance, and complement future advances in the technology. A prototype was fabricated with dimensions that were optimized for installation at a pilot site. Selection criteria for the pilot site included (1) a detention basin that was representative of a conventional flood control design from a developed site with a relatively large portion of impervious area (~50%); (2) an immediate receiving stream network that drained a relatively small watershed with preferably an individual channel dominated by the detention basin outflow; and (3) a willing property owner.

We followed standard hydrogeomorphic field data collection (Harrelson *et al.,* 1994; Bunte and Abt, 2001) and modeling (Julien, 1998) methods as described in detail by Hawley and Vietz (2016) to estimate Q_{critical} for bed material mobility in the receiving stream network. Due to the high sensitivity of Q_{critical} to both channel slope and bed material size, data were collected at three sites in the immediate receiving stream network in order to have greater confidence in the Q_{critical} estimate. Because channel roughness varies with seasons and flow depth, we used a gradient of Manning n values (0.048-0.132) to model hydraulics after Hawley *et al.* (2012b). Similarly, we used a range of dimensionless critical shear stress values (0.03-0.54) to model incipient motion of the median bed material particle (d_{50}) because there are limited flume data that are comparable to the Northern Kentucky stream setting (*i.e.,* disc-shaped bed material composed of angular limestone particles in the coarse gravel/small cobble range). We then used the lower limit of the 95% confidence interval of the mean Q_{critical} estimate for each site as the representative value to consider when determining design targets after Hawley *et al.* (2012b). In order to make the absolute Q_{critical}

estimates transferable between sites, we standardized the values by expressing them as a fraction of the predeveloped two-year peak flow (Q_2) after Watson *et al.* (1997). Q_2 was estimated using the U.S. Geological Survey regional equations after Hodgkins and Martin (2003).

We used an industry standard hydrologic/hydraulic modeling program for detention basins (HydroCAD version 10.00-12, HydroCAD Software Solutions, Chocorua, New Hampshire) to model four scenarios including (1) predeveloped conditions (*i.e.,* predeveloped); (2) postdeveloped conditions without a detention basin (i.e., postdeveloped); (3) postdeveloped conditions with a conventional detention basin prior to the retrofit installation (*i.e.*, preretrofit); and (4) postdeveloped conditions with a retrofit detention basin (*i.e.*, postretrofit). HydroCAD was selected over potentially more robust modeling platforms because of its dominance in the stormwater practitioner community (*i.e.*, by using a ubiquitous model among detention basin designers, we hoped to promote greater acceptance of the retrofitting concept by practitioners). Standard design storm analyses were used to optimize the size and configuration of the retrofit device such that outflow was restricted to a discharge that was less than Q_{critical} for as many design storms as possible up to the two-year storm, while maintaining the preretrofit level of service for the 100-year storm (*e.g.*, if the 100-year storm was fully contained within the basin under the preretrofit scenario, it should also be contained within the basin under the postretrofit scenario). The model was also used to predict longer-term results, such as a comparison of the cumulative effect of the top 22 events over a 40-year National Oceanic and Atmospheric Administration (NOAA) rainfall record (1953-1992), as well as the top 71 events in the “typical” rainfall year for the region from 1970 (*i.e.*, all events greater than 0.25 cm). Previous modeling efforts had documented that the top 22 events from a 40-year record as the most likely events for causing bed material mobility in the regional setting (Hawley *et al.,* 2012b) such that a continuous rainfall runoff model was unnecessary for the purposes of this analysis (the validity of this assumption was further demonstrated by the results presented herein). Sediment transport capacity was modeled using the Meyer-Peter and Müller (1948) volumetric bed-load equation (Chien, 1956) with corrected parameters from Wong and Parker (2006). Following the detailed procedure of Hawley and Bledsoe (2013), flows were binned into histograms and normal depth hydraulics were simplified by using hydraulic geometry functions of the receiving stream geometry after Buhman *et al.* (2002).

Monitoring of the retrofit performance was conducted using a suite of time-series data including (1) time-series photographs of basin stage; (2) outflow and inflow pipe discharge (via area-velocity meters); (3) stream stage gages; and (4) rain gages (Figure 2). Photos of the outlet structure were taken at 10-min intervals via a staff-mounted trail camera. A staff gage mounted at the inlet to the retrofit device was used to provide a scale for the photos.

Initially, two, and ultimately three pipe-flow meters (ISCO model 2150) were donated to the project by Teledyne Isco and recorded measurements at 15-min intervals. The gages were installed according to the manufacturer’s specifications and data were downloaded and processed using their software (Flowlink 5.1, Teledyne Isco, Lincoln, Nebraska) and protocols. These data are typically considered to have precision of ±2%, with the exception of extremely low flows, which go unrecorded due to minimum depths that are required for accurate area-velocity measurements to register.

Time-series stage data were collected using "level logger" pressure transducers that were installed at the same three reaches in the receiving stream network that were used for geomorphic data collection. The immediate receiving channel, termed the "spur," served as the experimental reach as its catchment was predominantly comprised of the same drainage area of the detention basin (*i.e.,* 9.1 ha of 12.7 ha). Two additional gages were placed in the spur's immediate receiving channel — one upstream of the confluence serving as the control site (DA = 70.3 ha), and one downstream of the confluence to monitor the network effect of the retrofit (DA = 87.4 ha). These pressure data were recorded every 15 min and converted into stream stage using the manufacturer's software, which included a correction for atmospheric pressure. Data were screened for outliers, and values that were determined to be erroneous, such as points that were recorded during data downloads when the transducers were out of the water, were systematically removed.

An Isco 4150 Flow Logger, also donated by Teledyne Isco, was installed at the site and collected incremental rainfall at 10-min intervals. Hourly precipitation data from a NOAA station located at the Cincinnati/Northern Kentucky International Airport, which was less than about 2 km away from the site, served to validate the site data. Flow into the detention basin included two pipe inlets and one swale, along with direct precipitation and local drainage. The outflow of the basin was routed through a network of staged pipes that were connected to a single 81-cm-diameter outflow pipe on the downstream side of the berm. The basin was designed for flows greater than the 100-year design event to discharge through a concrete spillway. Access to monitoring equipment was limited by grant funding phases and timing of equipment donations, such that we deployed the equipment as it became available. The initial pipe monitoring deployment included installations on the downstream side of the 81-cm outflow pipe and on one of the two inflow pipes to the basin. When the third gage became available, the second inflow pipe was also gaged. All other inputs into the basin, including the swale and local drainage remained ungaged.

In order to compare the postretrofit performance to preretrofit conditions, we primarily used event-based analysis that included the detention basin monitoring data and modeling results. Events were screened to remove those affected by snowmelt or frozen conditions such that the only source of stormwater runoff for the event in question was rainfall from that event. In addition, probability distribution frequency (PDF) analyses of comparable record lengths were used to assess the influence of the retrofit on the receiving stream stage. These stage data were standardized by dividing incremental measurements by the average stage value from the record. Installation of the prototype occurred on December 21, 2013, with approximately six to nine months of preretrofit data (depending on data type), and postretrofit data collection that remained ongoing through July 6, 2015.

RESULTS

The pilot installation is located at a Toyota parts distribution facility that met the site objectives mentioned above, with a contributing drainage area of 9.1 ha of which ~50% were impervious surfaces (consisting primarily of industrial building rooftop and parking lots), and a receiving channel with flow dominated by the detention basin outflow. In the subsections below, we present a weight of evidence that demonstrates the hydrologic benefits of the retrofit device, including decreased frequency and durations of bed-mobilizing and high-stage flows in receiving streams, as well as prolonged storage times within the basin that could potentially improve water quality processes.

Estimating a Q_{critical} Design Target

The lower bound of the 95% confidence interval of the mean Q_{critical} estimate for the incipient motion of the d_{50} in the receiving stream network was 70, 50, and 30% of Q_2 for the spur, upstream, and downstream sites, respectively. Although this implies that the spur site may have been stable at flows up to 70% of the two-year flow, we selected a design target of 40% of Q_2 to be more conservative. Demonstrating a proof of concept at this level of flow restriction was also important when evaluating the potential for implementation of the retrofit strategy across the Northern Kentucky region because 40% of Q_2 was consistent with a broader regional estimate of Q_{critical} from 23 regional sites (Sustainable Streams, "Development of a Regionally-Calibrated Q_{critical} for Storm Water Management," unpublished technical report for Sanitation District No. 1, 2012). This made the Q_{critical} design target for the detention basin outflow 0.38 m^3/s, based on the Q_2 estimate of 0.95 m^3/s for the predeveloped design storm.

Optimizing the Retrofit Device

Using an iterative design process and standard design storm hydrology, an approximate restriction of 75% of the 61-cm-diameter low-flow outlet in combination with a 46-cm-diameter staged bypass (130 cm above the invert of the low-flow outlet) enabled the restriction of all design storms up to the two-year storm to be released below the Q_{critical} target (Figure 3). The net effect was to use approximately 19 cm of excess freeboard at the 100-year design storm in order to convert the three-month, six-month, and one-year design storms from events that had previously exceeded Q_{critical} to events that were not anticipated to exacerbate downstream erosion (Table 1). In doing so, the configuration maintained the preretrofit level of service for the 100-year design storm, such that it remained fully contained within the detention basin. Furthermore, an existing concrete spillway provided a designed overflow in the event that the water surface reached its invert during an extreme event

Model Results

The HydroCAD model we developed to design and optimize the retrofit device was also used to simulate performance over longer rainfall records. Analysis of the top 22 storms over a 40-year rainfall record showed only 2.1 m tons of cumulative sediment transport capacity under predeveloped conditions (Figure 4). Under postdeveloped conditions (*i.e.,* ~50% impervious) without any detention, the capacity to erode the receiving stream bed material increased by more than 30-fold to 73.0 metric tons. Conventional flood control detention (i.e., preretrofit) resulted in 38.3 metric tons of cumulative sediment transport capacity (nearly 20 times greater than predeveloped conditions). By contrast, the postretrofit scenario reduced the sediment transport capacity of the conventional design by more than 40% to

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22.4 metric tons (approximately 10 times greater than predeveloped conditions). It can be reasonably assumed that our decision to model only the top 22 events in the 40-year rainfall record did not inadvertently omit any potential Q_{critical} events for this network because 2 of the top 22 events were not modeled to exceed Q_{critical} under any scenario.

The model also predicts prolonged storage times in the postretrofit basin, which may have implications for improved water quality processing (such as increased ponding time available for sedimentation of suspended sediment). With an estimated 574 h of storage from 71 events in a typical year, the postretrofit basin is predicted to have nearly 42 h of additional detention than the conventional (preretrofit) flood control design of 532 h (Figure 5).

Basin Monitoring Results

Outflow pipe data have been collected since autumn of 2013 to March 2017, whereas the inflow pipe gage data were not available until after the device was installed on December 21, 2013. Rainfall intensity was used as a surrogate for basin inflow for the preretrofit record because it tracks extremely well with inflow during rainfall events (Figures 6b and d). Given the nature of a field study we did not have pre- and postretrofit events that were identical in all aspects such as rainfall intensity, total depth, and duration. Of a total of eight pre- and eight postretrofit events captured by the monitoring (after screening to remove events affected by snowmelt/frozen conditions), comparable pre- and postretrofit events were selected based on similar levels of rainfall intensity (Figures 6a and b), as well as similar peak outflow rates (Figures 6c and d).

Efforts were taken to select events that represented a fair comparison, erring on the side of not always selecting the events that looked most favorable for the device. For example, the postretrofit events depicted in Figure 6 were the highest recorded peak outflows (first and tied for second), whereas the preretrofit events ranked first and fifth. The intensities of the postretrofits in Figure 6 ranked first and tied for fifth, whereas the intensities of the preretrofit events ranked first and tied for second. The cumulative rainfall for the postretrofit events ranked first and third, whereas they ranked third and fifth for the preretrofit events. Finally, the durations for the postretrofit events were less than their paired preretrofit event such that they had less time to manage approximately double the volume.

In the first comparison, the preretrofit event (October 31, 2013) had a smaller peak rainfall intensity (2.40 cm/h) but larger peak discharge (0.17 m^3/s) than the postretrofit event (April 2, 2014, peak intensity 3.00 cm/h, peak discharge 0.15 m^3/s). The postretrofit event also received more than twice the total rainfall than the preretrofit event (5 cm compared 2.3 cm), adding to the weight of evidence of the restrictive effect of the retrofit device. In the second comparison from December 5, 2013 (preretrofit) to June 4, 2014 (postretrofit), the postretrofit event had nearly three times the peak rainfall intensity than the preretrofit event (6.60 cm/h *vs*. 2.40 cm/h) and double the cumulative rainfall (3.3 cm *vs*. 1.6 cm); but the same peak outflow as the preretrofit event (0.11 m^3/s). A more detailed depiction of the postretrofit event from June 4, 2014 (Figure 6d) is provided in Figure 7 with corresponding real-time photographs that highlight the 3 h of ponding that was induced by the retrofit device, resulting in a prolonged release of a peak discharge that was over five times less than the peak inflow (0.11 m^3/s compared to 0.58 m^3/s). In summary, the postretrofit events had greater rainfall depths, peak intensities, and shorter durations than the preretrofit events, but were discharged at less than or equal to the peak discharge of the preretrofit events.

Furthermore, these were not isolated cases of the device appearing to have an influence. Six of the eight postretrofit events had peak intensities ≥3 cm/h (including 3.0, 3.0, 3.6, 4.2, 5.4, and 6.6 cm/h), and of those only one event had a peak discharge >0.11 m^3/s (the April 2, 2014 event of 0.15 m^3/s discussed above), with events as low as 0.05 m^3/s (0.05, 0.07, 0.09, 0.11, 0.11, 0.15 m^3/s). By contrast, five of the eight preretrofit events had peak discharges ≥0.11 m^3/s (0.11, 0.13, 0.14, 0.14, 0.17 m^3/s), but their peak intensities (0.60, 2.4, 2.4, 2.4, 3.1 cm/h) showed very little overlap with the postretrofit events with only one event greater than 3 cm/h.

Basin Model Validation

The April 2, 2014 event (Figure 6b) was also used to assess the performance of the HydroCAD model we used during the optimization of the retrofit design, as well as predict the benefits relative to design storm performance (Figure 4) and typical year storage (Figure 5). Without any calibration to the monitoring data, the rainfall data were input into the HydroCAD model and used to predict the outflow hydrograph. The modeled and metered outflow hydrographs are presented in Figure 8, with similar shapes and peak flows (0.166 m^3/s *vs.* 0.150 m^3/s, respectively). A total of ten events were compared (five preretrofit and five postretrofit) using the model and flow meter data. The average error in peak outflow between the model and the meter was 37%; however, when two outlier events (one pre- and one postretrofit) were withheld, the average error improved to 7%.

Stream Monitoring Results

The influence of the retrofit device on receiving streamflows was captured by a series of pressure transducers in the immediate receiving stream network. Comparisons of the PDFs of water levels standardized by their mean value are presented in Figure 9 from preretrofit and postretrofit periods of nearly equal duration (*i.e.,* 288 days *vs.* 285 days), but with more intense precipitation observed during the postretrofit period (Table 2). Although changes are fairly consistent across the upper tails of the PDFs, we report results for the 1% exceedance value because it is these extreme discharges that are most likely to exceed Q_{critical}. At the upstream control site, the 1% flow depth increased from 2.07 times the average flow depth during the preretrofit period to 2.31 times the average depth during the postretrofit period. By contrast, standardized depths in the spur reach, immediately downstream of the detention basin outfall, decreased from 1.83 to 1.67 for the 1% occurrence interval. Values for the 1% standardized flow depth remained relatively unchanged at the downstream site (preretrofit = 1.63, postretrofit = 1.65). A decrease in the overall precipitation volume between periods (103 *vs.* 88 cm, Table 2) corresponded to decreased depths for the lower tail of the PDF at the upstream control site, with the 90% occurrence interval decreasing from 0.31 to 0.21 times the average depth. At the spur site, however, the 90th percentile depth substantially increased between monitoring periods from 0.12 to 0.69 times the average depth. Once again, the downstream site remained relatively unchanged, with the 90% occurrence interval

0.77 times the average depth during the preretrofit period and 0.72 during the postretrofit period.

DISCUSSION

A Weight of Evidence Demonstrates the Potential Benefits of Detention Basin Retrofitting

Through a combination of industry standard modeling, detention basin pipe-flow data, and receiving stream-stage data, we have presented a weight of evidence related to the potential benefits of simple detention basin outlet retrofit devices such as Detain H_2O. The pilot installation has demonstrated that the approach has the potential to reduce the frequency of streambed-eroding flows downstream of conventionally designed flood control basins. Similar to the type of routine modeling that would be used to size and optimize a new detention basin, the modeling approach used herein illustrates that existing basins can be retrofit to reduce the peak discharge of design storms such as the three-month, six-month, and one-year events to rates below Q_{critical}, while maintaining adequate levels of service for flood flows such as $Q100$.

Furthermore, monitoring in the receiving stream network showed that these effects were transferred downstream — stage at the 1% recurrence interval during the postretrofit monitoring period was lower in the immediate receiving stream (*i.e.,* spur), but higher in the control stream (*i.e.*, upstream, Figure 9). The net effect of these contrasting reaches was that downstream of their confluence, high-flow stages was essentially unchanged, indicating that the retrofit device was able to mitigate the effects of the increased precipitation intensities experienced during the postretrofit period at the downstream site (Table 2).

An added benefit of the retrofit approach includes prolonged storage times within the basin (Figure 5), which increases the potential for settling of suspended sediment (and any adsorbed nutrients) and provides additional pathogen exposure to naturally occurring UV radiation as well as nutrient cycling via increased contact time with the basin's vegetated surface. This implies that the approach has the potential to improve water quality both within the detention basin (via increased storage time) and in receiving streams (via decreased channel erosion). The reduced flashiness and prolonged baseflows (Figure 9) also point to the potential ecological benefits of the retrofitting.

Although instrument error is anticipated to be relatively minor (± 2%), our pre/postanalytical approach using data from the same equipment and monitoring locations provides a level of added confidence in these results. Furthermore, the deviation from our modeled and metered outflow can largely be explained by the "lip" on the retrofit device, which creates artificial ponding in the model at small depths (< ~0.25 cm), but in reality is released over a prolonged period through the funnel connection between the device and the existing pipe due to the lack of a water-tight seal (Figure 3). This "trickle" effect, which can be seen in the falling limb of the metered hydrograph in Figure 8, was considered to be an added benefit of the device in terms of prolonged baseflows; however, we did not incorporate it into the model in an effort to be conservative relative to meeting design storm criteria. For example, in both of the two outlier cases, the modeled peak discharge was higher than the metered peak discharge, suggesting a conservative model in terms of ensuring that peak discharges for design storms such as the 100-year event do not exceed the predeveloped peaks. Had the model been calibrated to better capture the “trickle” effect behavior, the modeled benefits related to prolonged detention time and reduced durations of channel-eroding discharges would have likely been larger than those reported in Figures 4 and 5 further underscoring the decision to err on the side of being conservative in our modeling approach.

Moving from the Pilot to a Network-Based Approach

Engineers and managers should use sound professional judgment and consult relevant stormwater rules and regulations and other applicable guidance from the jurisdictional utility when evaluating the feasibility of retrofitting existing detention basins to meet acceptable standards of care with their retrofit designs. For example, if a detention basin was substantially undersized (such as reaching capacity at Q_{10}) and did not have a designed spillway to provide safe passage of overtopping events, retrofit strategies might be prioritized to first bring the basin to an acceptable level of service in terms of flood control and safety, and then evaluate the potential for adding channel protection benefits as a second priority

To that end, it would be in the best interest of a stormwater utility to take network-based approach to retrofitting in order to optimize retrofits for maximum benefit to the receiving stream network. In addition, not all basins will have similar levels of excess freeboard, such that the relative effectiveness of individual retrofits will likely vary by basin. In Northern Kentucky, for example, a review of eight conventionally designed detention basins showed that they tended to have ~10% excess capacity relative to the regional standards, but the level of excess storage was not uniform. For example, we have identified basins with up to 40% excess storage capacity, such that retrofitting targets might be able to reduce nearly all design flows to less than the Q_{critical} target and help to compensate for the lack of retrofitting capacity in proximate basins throughout the network. Finally, the level of customization to each detention basin will likely increase the benefits of individual retrofits; however, one can envision some standard restriction levels for standard pipe sizes that might provide cost savings over excessively tailored designs.

Economics Point to Retrofitting as a Stormwater Management Tool for Addressing Instream Erosion

With materials, design, and implementation estimated to be on the order of $10,000 per basin, perhaps one of the strongest arguments for implementing a detention basin retrofit program is financial. In the pilot installation, the detention basin captured a drainage area of 9.1 ha, which scales to a unit cost of ~$110,000 per km^2 and is about two orders of magnitude less than stormwater retrofitting programs that use more distributed green infrastructure practices and approximately one order of magnitude less than constructing new detention basins (Table 3). Two of the largest reasons that help to explain why detention basin retrofits are more economical than construction of new best management practices are that, first, stormwater is already routed to these existing facilities, and secondly, additional earthwork (and the associated erosion control and revegetation efforts) is unnecessary with this approach. Maintenance is an important consideration for detention basin retrofits; however, it is important to keep in mind that routine inspection and maintenance of existing detention basins is already a feature of many stormwater management programs, whereas construction of new BMPs adds new sites and maintenance regimes to existing maintenance programs. Property access is another potentially limiting factor with any stormwater retrofit program, but stormwater utilities typically already have access to existing detention basins, whereas property access for the construction of new BMPs in previously developed neighborhoods is often limited

Converting Existing Assets from Channel Erosion Liabilities to Stream Rehabilitation Solutions

Hydromodification, including excess channel erosion from inadequately managed stormwater, is one of our nation's leading stream impairments (USEPA, 2009). Conventional detention basins are relatively ubiquitous stormwater assets that typically do not adequately protect streams from hydromodification. For example, despite being designed to comply with the peak-matching standards of its time, detention basin outflow at the pilot study site exceeded the critical flow for much longer durations and resulted in ~20 times greater sediment transport capacity than the predeveloped setting (Figure 4).

This study underscores the fact that these existing assets can become a cost-effective means for reducing the impacts of hydromodification. With limited cost or complexity, simple retrofit devices such as Detain H_2O can substantially reduce the sediment transport capacity of these ubiquitous facilities (~42% reduction in this application). In concept, retrofitting enough existing detention basins to restore a more natural disturbance regime across a stream network could help to facilitate a transition from the typically unstable states that urban streams tend to occupy (*i.e.,* stages 2, 3, and 4 of the CEM) to a new equilibrium (*i.e.,* CEM stage 5, Figures 10 and 11, Schumm *et al.,* 1984). Improving channel stability and habitat in urban streams via stormwater management measures not only has the potential to be much more economical than in-channel stream restoration (typically on the order of ~ $650 per m, Table 3) but also has the potential to impact additional drivers of urban stream impairments, such as the flashy flow regime and poor water quality (Booth, 2005; Harman *et al.,* 2012). Indeed, it is these bottom-up, watershed-based strategies that have been demonstrated to show instream biological results in case studies that include agricultural watersheds (Wang *et al.,* 2002), and more recently, in some urban/suburban settings (Smucker and Detenbeck, 2014), whereas in-channel restoration efforts tend to show little difference from biological communities of nonrestored urban streams, with one study finding only 2 of 78 projects with significant increases in biodiversity (Palmer *et al.,* 2010).

In this light, detention basin retrofits could become a cost-effective tool for stormwater utilities with mandates related to their Municipal Separate Storm Sewer System (MS4) programs and/or impervious area retrofitting requirements related to Total Maximum Daily Loads for sediment and/or phosphorus that have sources attributable to stream channel erosion. The approach could contribute to reduced sediment loads via decreased bed sediment transport and reduced bed and bank erosion, and potentially reduced phosphorus transport in cases where it was adsorbed to channel sediment particles. For example, Montgomery County, Maryland's planned expenditures to comply with their program permits related to Chesapeake Bay load reductions were reported as $305M to retrofit 1,720 ha of previously untreated impervious area (20% of its total untreated impervious area) between 2010 and 2015, with similar goals anticipated over subsequent five-year cycles in order to ultimately achieve retrofitting of 100% of the previously uncontrolled impervious area (Brown and Curtis, 2012). These unit costs, on the same order of those reported by King County (2013, Table 3), might be reduced if there were opportunities to deploy detention basin retrofits as a part of an overall impervious area retrofit program. Doing so could potentially contribute to lower stormwater utility expenditures as well as improved biological, chemical, and physical integrity of our nation's streams — the ultimate goal of the Clean Water Act.

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LITERATURE CITED

Bledsoe BP, 2002 Stream Erosion Potential Associated with Stormwater Management Strategies. Journal of Water Resources Planning and Management 128(6):451–455, 10.1061/(ASCE)0733-9496(2002)128:6(451).

Booth DB, 2005 Challenges and Prospects for Restoring Urban Streams: A Perspective from the Pacific Northwest of North America. Journal of the North American Benthological Society 24(3): 724–737, 10.1899/04-025.1.

Brown T and Curtis M, 2012 Integrated Watershed Restoration to Achieve Local and Chesapeake Bay Wasteload Allocations In: Proceedings of the Water Environment Federation Stormwater Symposium, L. Jaworski and W. Tam (Editors). Water Environment Federation, Baltimore, Maryland, pp. 289–303.

Buhman DL, Gates TK, and Watson CC, 2002 Stochastic Variability of Fluvial Hydraulic Geometry: Mississippi and Red Rivers. Journal of Hydraulic Engineering 128(4):426–437, 10.1061/(ASCE)0733-9429(2002)128:4(426).

Bunte K and Abt SR, 2001 Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-Bed Streams. Journal of the American Water Resources Association 37(4):1001–1014, 10.1111/j.1752-1688.2001.tb05528.x.

Chien N, 1956 The Present Status of Research on Sediment Transport. Transactions of the American Society of Civil Engineers 121:833–868.

King County, 2013 Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: SUSTAIN Model Pilot Study King County Department of Natural Resources and Parks, Seattle, Washington.

Emerson CH, Welty C, and Traver R, 2003 Application of HEC-HMS to Model the Additive Effects of Multiple Detention Basins Over a Range of Measured Storm Volumes World Water & Environmental Resources Congress 2003 and Related Symposia. American Society of Civil Engineers, Philadelphia, Pennsylvania, pp. 56–68.

Eng K, Wolock DM, and Carlisle DM, 2013 River Flow Changes Related to Land and Water Management Practices Across the Conterminous United States. Science of the Total Environment 463-464:414–422, 10.1016/j.scitotenv.2013.06.001. [PubMed: 23827362]

Guo JCY, 2008 Retrofitting Detention Basin with Water Quality Control Pool. Journal of Irrigation and Drainage Engineering 135(5):671–675, 10.1061/(ASCE)IR.1943-4774.0000051.

Harman W, Starr R, Carter M, Tweedy K, Clemmons M, Suggs K, and Miller C, 2012 A Function-Based Framework for Stream Assessment and Restoration Projects U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, D.C., EPA 843-K-12–006.

Harrelson CC, Rawlins CL, and Potyondy JP, 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RMGTR-245 U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, 61 pp., https://www.fs.usda.gov/treesearch-beta/pubs/20753.

Hawley RJ and Bledsoe BP, 2013 Channel Enlargement in Semi-Arid Suburbanizing Watersheds: A Southern California Case Study. Journal of Hydrology 496:17–30, 10.1016/j.jhydrol.2013.05.010.

Hawley RJ, Bledsoe BP, Stein ED, and Haines BE, 2012a Channel Evolution Model of Semiarid Stream Response to Urban-Induced Hydromodification. Journal of the American Water Resources Association 48(4):722–744, 10.1111/j.1752-1688.2012.00645.x.

Hawley RJ, MacMannis KR, and Wooten MS, 2013a Bed Coarsening, Riffle Shortening, and Channel Enlargement in Urbanizing Watersheds, Northern Kentucky, U.S.A Geomorphology 201:111–126, 10.1016/j.geomorph.2013.06.013.

Hawley RJ, MacMannis KR, and Wooten MS, 2013b How Poor Stormwater Practices Are Shortening the Life of Our Nation’s Infrastructure-Recalibrating Stormwater Management for Stream Channel Stability and Infrastructure Sustainability In: Proceeding of the World Environmental and Water Resources Congress. American Society of Civil Engineers, Environmental and Water Resources Institute, Cincinnati, Ohio, pp. 193–207.

Hawley RJ and Vietz GJ, 2016 The Urban Disturbance Regime: Addressing the Urban Stream Disturbance Regime. Freshwater Science 35(1):278–292, 10.1086/684647.

Hawley RJ, Wooten MS, MacMannis KR, and Fet EV, 2016 When Do Macroinvertebrate Communities of Reference Streams Resemble Urban Streams? The Biological Relevance of $Q_{critical}$. Freshwater Science 35(3):778–794, 10.1086/687808.

Hawley RJ, Wooten MS, Vatter BC, Onderak E, Lachniet MJ, Schade T, Grant G, Groh B, and DelVerne J, 2012b Integrating Stormwater Controls Designed for Channel Protection, Water Quality, and Inflow/Infiltration Mitigation in Two Pilot Watersheds to Restore a More Natural Flow Regime in Urban Streams. Watershed Science Bulletin 3(1):25–37.

Hodgkins GA and Martin GR, 2003 Estimating the Magnitude of Peak Flows for Streams in Kentucky for Selected Recurrence Intervals. U.S. Geological Survey Water-Resources Investigations Report 03–4180, 73 pp. http://pubs.usgs.gov/wri/wri034180/.

Julien PY, 1998 Erosion and Sedimentation. Cambridge University Press, Cambridge, England, ISBN-13: 978–0521636391.

Konrad CP and Booth DB, 2002 Hydrologic Trends Associated with Urban Development for Selected Streams in the Puget Sound Basin, Western Washington. U.S. Geological Survey

Water-Resources Investigations Report 02–4040, 40 pp., http://pubs.usgs.gov/wri/wri024040/pdf/WRIR02-4040.pdf.

MacRae CR, 1997 Experience from Morphological Research on Canadian Streams: Is Control of the Two-Year Frequency Runoff Event the Best Basis for Stream Channel Protection? In: Effects of Watershed Development and Management on Aquatic Ecosystems Proceedings, L.A. Roesner (Editor). ASCE, Snowbird, Utah, pp. 144–162.

Marcoon K and Guo Q, 2004 Detention Basin Retrofit: Optimization of Water Quality Improvement and Flood Control. Critical Transitions in Water and Environmental Resources Management In: Proceedings of the 2004 World Water and Environmental Resources Congress, Gerald Sehlke Donald F. Hayes, and David K. Stevens (Editors). ASCE, Salt Lake City, Utah, pp. 1–10, 10.1061/40737(2004)43.

Meyer-Peter E and Müller R, 1948 Formulas for Bed-Load Transport In: Proceedings of the 2nd Meeting International Association for Hydraulic Research, Stockholm, Sweden, pp. 39–64. https://repository.tudelft.nl/islandora/object/uuid:4fda9b61-be28-4703-ab06-43cdc2a21bd7/?collection=research.

NRC (National Research Council), 2009 Urban Stormwater Management in the United States The National Academies Press, Washington, D.C., ISBN-13: 978–0309125390.

Palmer MA, Menninger HL, and Bernhardt E, 2010 River Restoration, Habitat Heterogeneity and Biodiversity: A Failure of Theory or Practice? Freshwater Biology 55:205–222, 10.1111/j.1365-2427.2009.02372.x.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, and Stromberg JC, 1997 The Natural Flow Regime: A Paradigm for Conservation and Restoration of River Ecosystems. BioScience 47(11):769–784.

Poff NL, Bledsoe BP, and Cuhaciyan CO, 2006 Hydrologic Variation with Land Use across the Contiguous United States: Geomorphic and Ecological Consequences for Stream Ecosystems. Geomorphology 79(3–4):264–285, 10.1016/j.geomorph.2006.06.032.

Pomeroy CA, Postel NA, O'Neill PA, and Roesner LA, 2008 Development of Stormwater Management Design Criteria to Maintain Geomorphic Stability in a Kansas City Metropolitan Area Stream. Journal of Irrigation and Drainage 134:562–566, 10.1061/(ASCE)0733-9437(2008)134:5(562)#sthash.l6MKVTTl.dpuf.

Postel N, Pomeroy C, Jacobs T, and Karuppasamy E, 2009 Analyzing the Impacts of a Retrofit Detention Basin Flow Control Strategy on Biodiversity in an Urban Stream SystemIn: World Environmental and Water Resources Congress 2009: Rivers Great, Starrett Steve (Editor). ASCE, Kansas City, Missouri, pp. 1–7.

Rohrer CA and Roesner LA, 2006 Matching the Critical Portion of the Flow Duration Curve to Minimize Changes in Modeled Excess Shear. Water Science and Technology 54:347–354, 10.2166/wst.2006.590. [PubMed: 17120668]

Roy AH, Wenger SJ, Fletcher TD, Walsh CJ, Ladson AR, Shuster WD, Thurston HW, and Brown RR, 2008 Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States. Environmental Management 42:344–359, 10.1007/s00267-008-9119-1. [PubMed: 18446406]

Schumm SA, Harvey MD, and Watson CC, 1984 Incised Channels: Morphology, Dynamics, and Control Water Resources Publications, Littleton, Colorado, ISBN-13: 978–1887201643.

Smucker NJ and Detenbeck NE, 2014 Meta-Analysis of Lost Ecosystem Attributes in Urban Streams and the Effectiveness of Out-of-Channel Management Practices. Restoration Ecology 22(6):741–748, 10.1111/rec.12134.

Townsend CR, Scarsbrook MR, and Doledec S, 1997 Quantifying Disturbance in Streams: Alternative Measures of Disturbance in Relation to Macroinvertebrate Species Traits and Species Richness. Journal of the North American Benthological Society 16(3):531–544, 10.2307/1468142.

USEPA (U.S. Environmental Protection Agency), 2009 National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle U.S. Environmental Protection Agency, Washington, D.C., EPA 841-R-08–001.

Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, and II Morgan RP, 2005 The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. Journal of the North American Benthological Society 24(3):706–723, 10.1899/04-028.1.

Wang L, Lyons J, and Kanehl P, 2002 Effects of Watershed Best Management Practices on Habitat and Fish in Wisconsin Streams. Journal of the American Water Resources Association 38(3):663–680, 10.1111/j.1752-1688.2002.tb00988.x.

Watson CC, Dubler D, and Abt SR, 1997 Demonstration Erosion Control Project Report Design Hydrology Investigations, Fort Collins, Colorado, submitted to U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Wong M and Parker G, 2006 Reanalysis and Correction of Bed-Load Relation of Meyer-Peter and Müller Using Their Own Database. Journal of Hydraulic Engineering 132(11):1159–1168, 10.1061/(ASCE)0733-9429(2006)132:11(1159)#sthash.C5JMyLyE.dpuf.

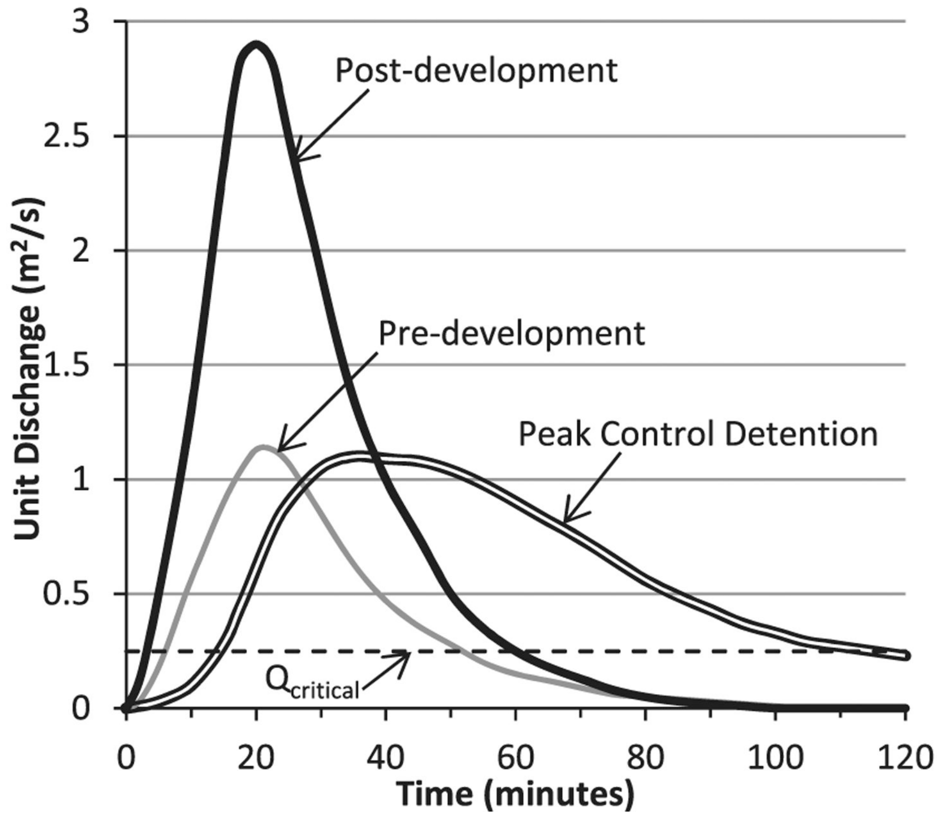

FIGURE 1.
Hydrograph Analysis for Conventional Detention of the Two-Year, 2-h Event in Fort Collins, Colorado (Adapted from Bledsoe, 2002).

FIGURE 2.
Pilot Installation Detention Basin (white and green oval) with Pipe Inflow and Outflow, Camera, Rain Gage, and Receiving Stream Monitoring Locations. Inflow from a swale entering from the east of the basin was ungaged.

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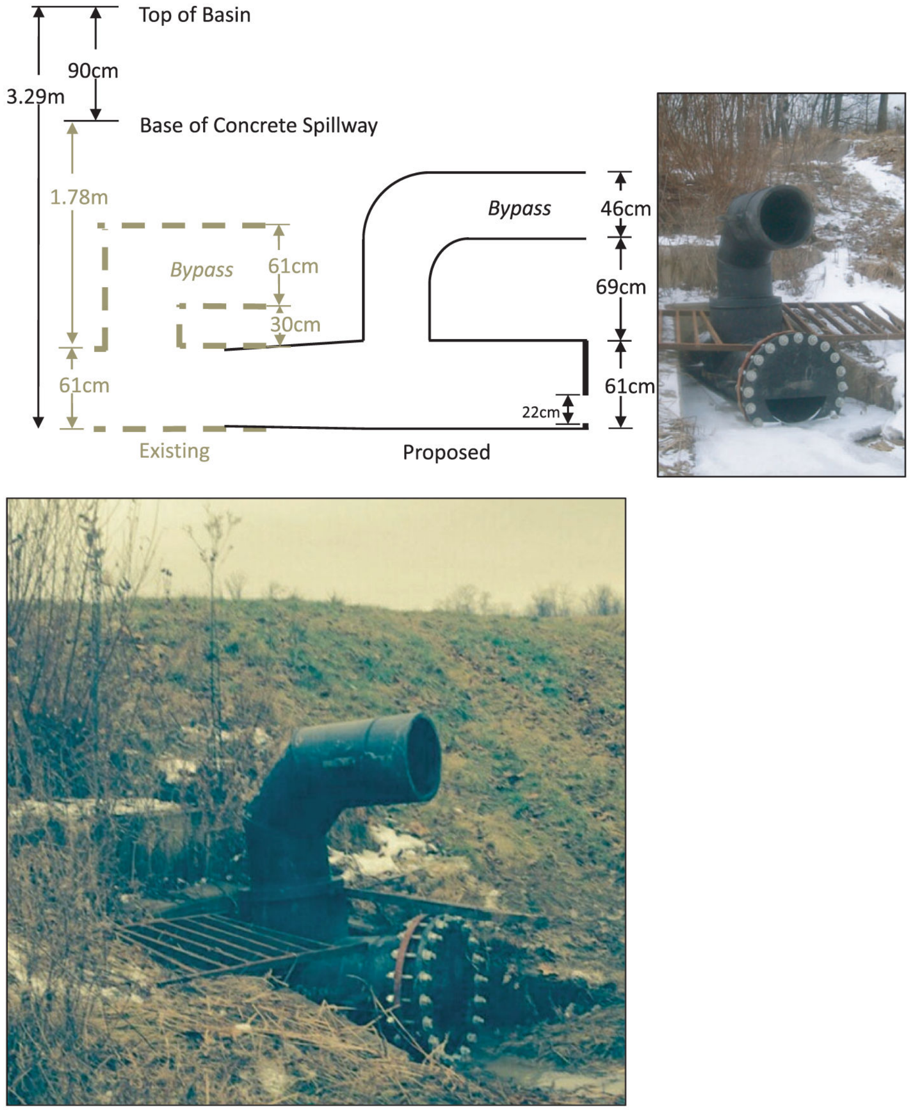

FIGURE 3.
Design Schematic and Photos of Detain H_2O Retrofit Device Pilot Installation.

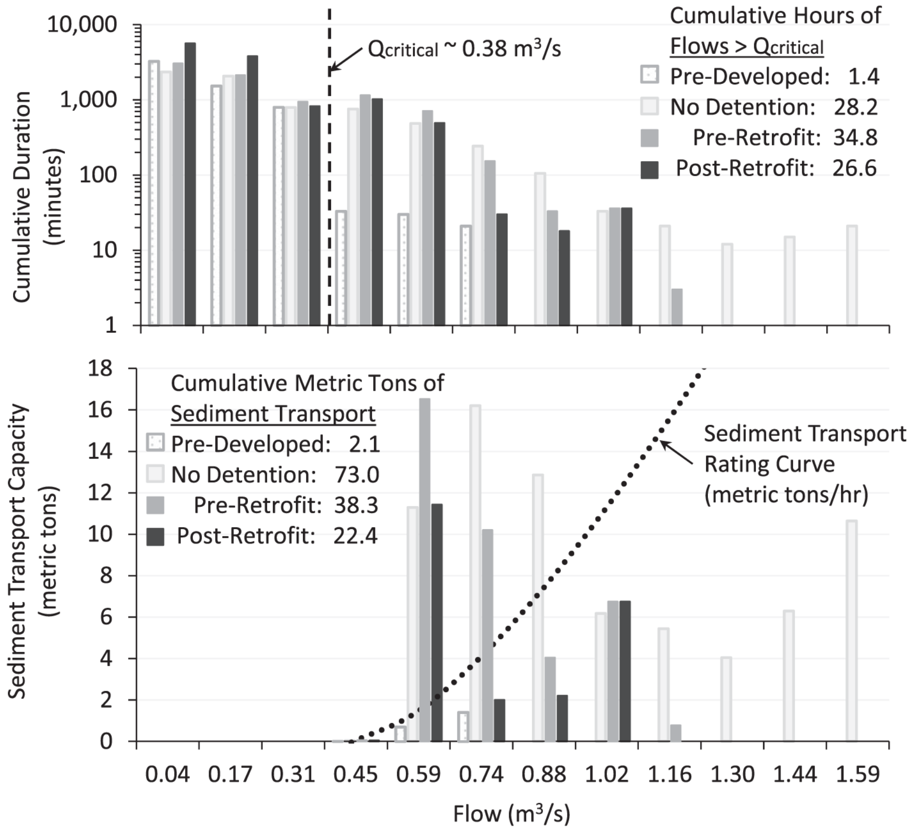

FIGURE 4.

Cumulative Flow Duration and Sediment Transport Capacity of the Top 22 Rainfall Events in a 40-Year Record (1953-1992) Show that by Reducing the Duration of Flows That Exceed Q_{critical} the Detention Outlet Retrofit Reduces the Sediment Transport Capacity of the Preretrofit Conditions by >40%.

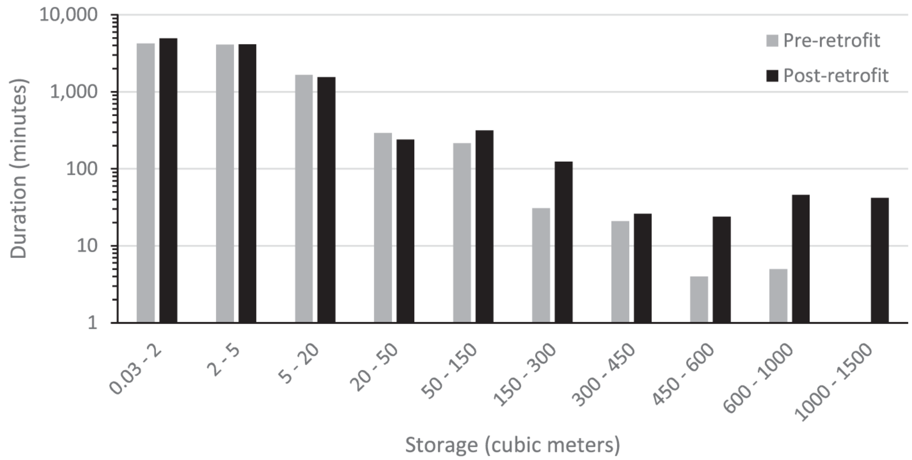

FIGURE 5.

Cumulative Duration of Detention Basin Storage for All 71 Events with Rainfall Depths >0.25 cm from the Typical Rainfall Year of 1970 Predict More than 40 Additional Storage Hours between Preretrofit and Postretrofit Scenarios.

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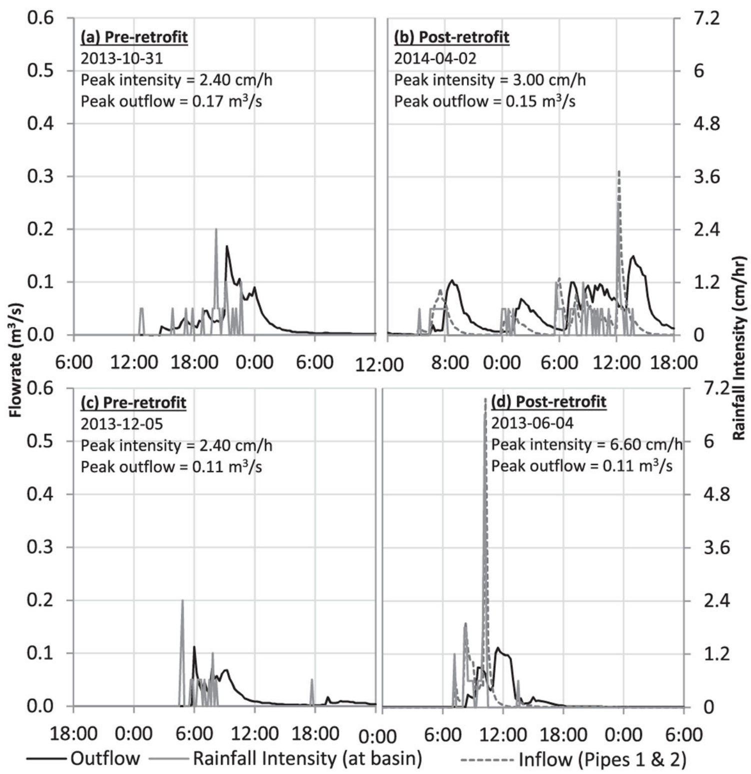
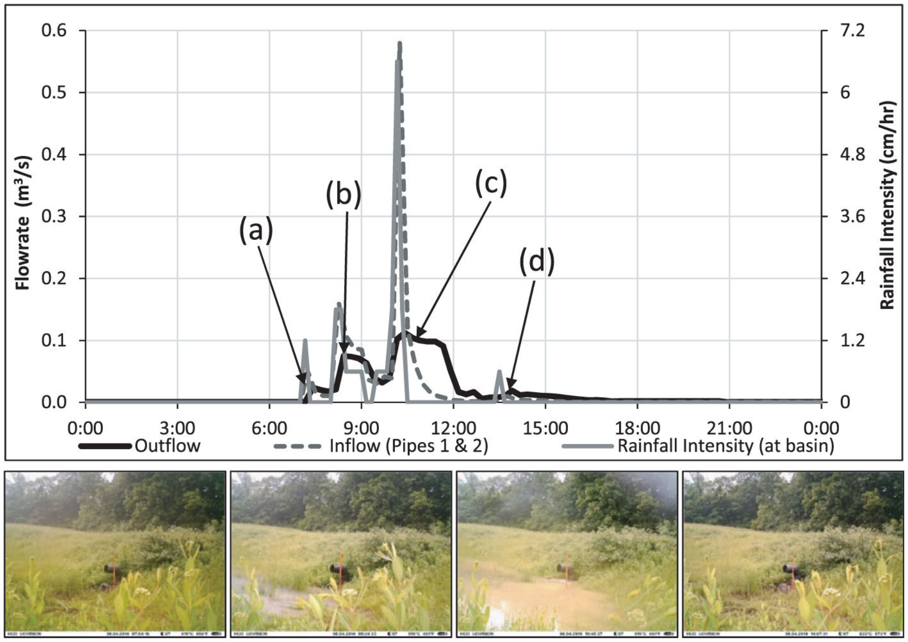


FIGURE 6.

Comparison of Preretrofit (left) and Postretrofit (right) Pipe Flow Hydrographs from Events with Comparable Peak Precipitation Intensity (top) and Peak Outflow (bottom) Demonstrates the Restrictive Effect of the Retrofit Device.



(a) 2014/06/04 – 7:54 (b) 2014/06/04 – 8:34 (c) 2014/06/04 – 10:45 (d) 2014/06/04 – 14:07

FIGURE 7.

June 4, 2014 Postretrofit Event with Hydrograph and Associated Photographs Indicating a Clear Increase in Basin Storage and Restriction of the Outflow due to the Full Submergence of the Restricted Low-Flow Pipe Outlet.

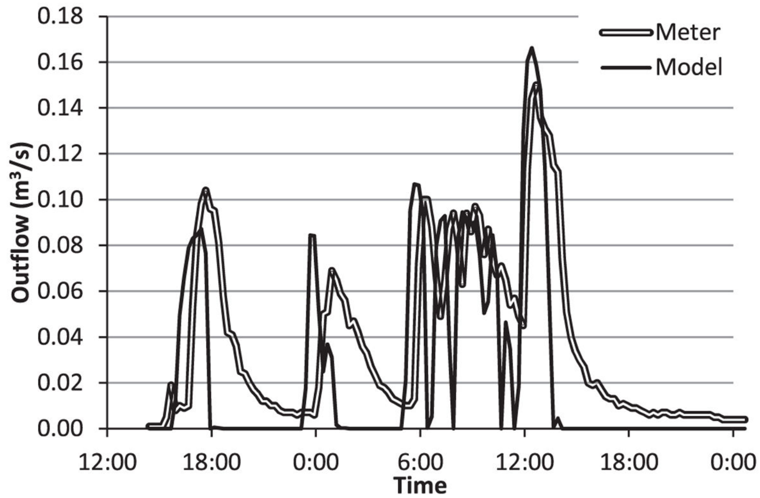


FIGURE 8.

Outflow Hydrographs from the April 3, 2014 Event That Compare the HydroCAD Model (using measured rainfall) to the Metered Data Show Relative Agreement in Terms of Shape and Peak Discharge.

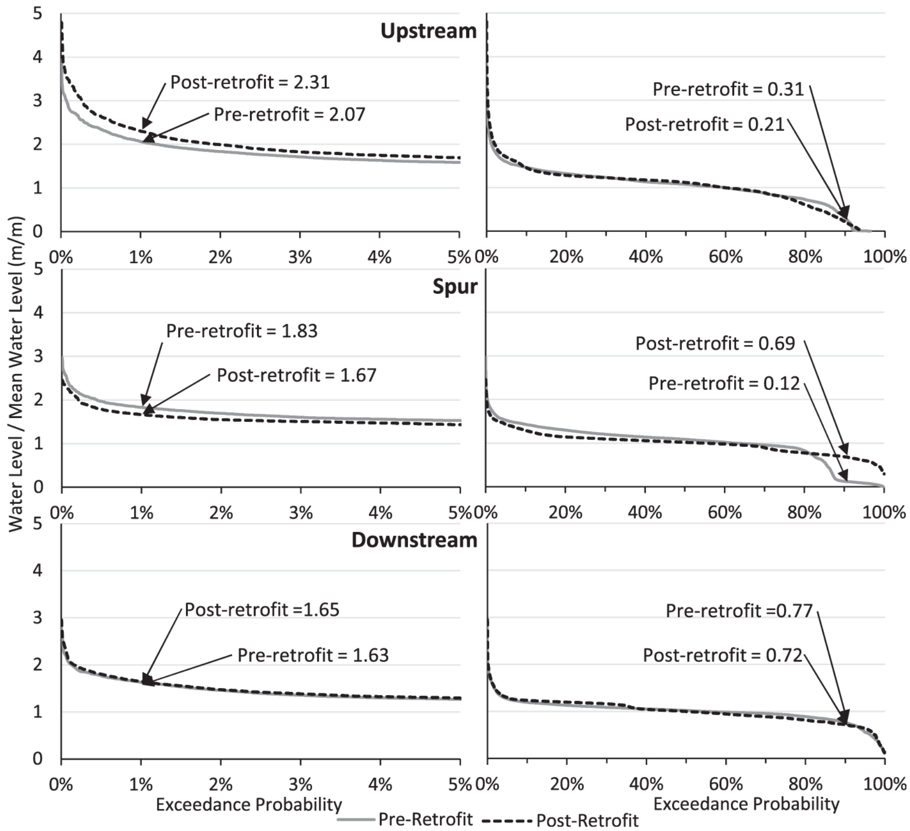


FIGURE 9.

Probability Distribution Frequencies (PDFs) of Water Level Standardized by Mean Water Level at Upstream (control), Spur (pilot), and Downstream Locations from Preretrofit (288 days) and Postretrofit (285 days) Analysis Periods, with Values for the 1 and 90% Exceedance Probability Flows in the Left and Right Figures, Respectively. The increase in the 1% depth at the upstream control site (top left) was likely attributable to more intense precipitation during the postretrofit period (Table 2), whereas the decrease in the 1% depth at the spur site (middle left) was likely attributable to the retrofit device. By contrast, less overall precipitation volume during the postretrofit periods (Table 2) explains the decrease in baseflows observed at the upstream control site (top right), whereas the clear increase in baseflows at the spur site (middle right) is likely attributable to the retrofit device. The net effect at the downstream site (bottom row) was a relatively unchanged PDF despite the differences in precipitation.

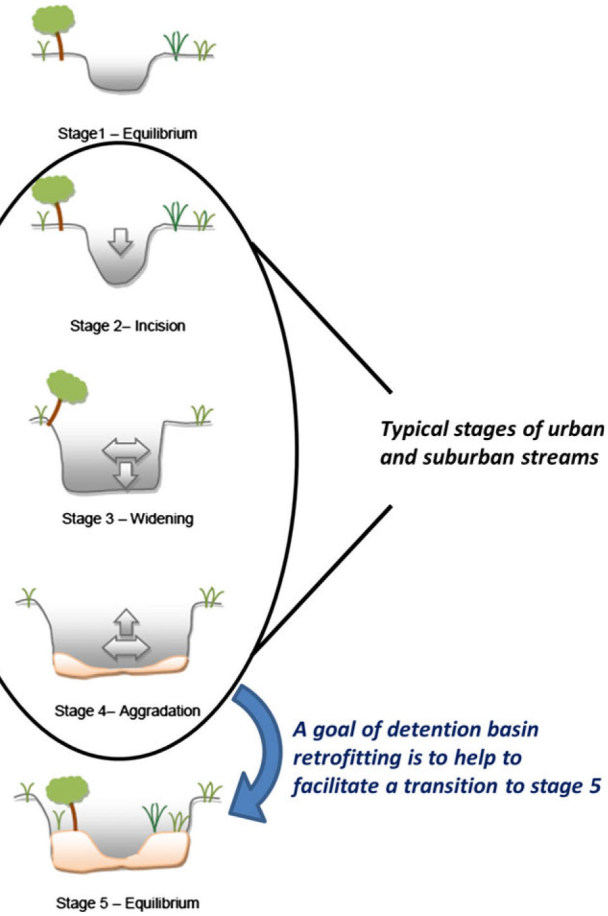


FIGURE 10.

One of the Ultimate Goals of Retrofitting Conventional Detention Basins for Improved Downstream Stability Is to Help to Facilitate a Transition from the Unstable Stages That Urban Streams Typically Occupy (stages 2, 3, and 4) to a New Equilibrium State (stage 5). Channel evolution model adapted from Schumm *et al.* (1984) and Hawley *et al.* (2012a).

FIGURE 11.

Sediment Deposition at the Bank Toe, Bar Building, and Colonization by Vegetation, Especially More Permanent Vegetation Such as the 2 Two-Year-Old Green Ash Trees (*Fraxinus pennsylvanica*) in the Right Foreground of This Reach of Upper Banklick Creek in the Northern Kentucky Study Region, Are the Types of Changes That Would Be Indicative of an Eventual Transition toward Channel Evolution Model (CEM) Stages 4-5 (equilibrium).

TABLE 1

Modeled Peak Discharges (m^3/s) for the Respective 24-h Design Storms Predict that the Retrofit Device Reduces the Three-Month, Six-Month, and One-Year Storms (bold text) Such That They No Longer Exceed the Q_{critical} Design Target.[1]

		Postdeveloped Conditions		
Return Period	**Predeveloped Conditions**	**Detention Basin Inflow**	**Preretrofit Outflow**	**Postretrofit Outflow**
3-month	0.14	0.88	**0.43**	**0.19**
6-month	0.34	1.26	**0.51**	**0.22**
1-year	0.63	1.69	**0.60**	**0.25**
2-year	0.95	2.12	0.67	0.47
10-year	1.93	3.28	1.00	0.91
25-year	2.58	3.97	1.22	1.11
50-year	3.10	4.52	1.37	1.25
100-year	3.67	5.10	1.50	1.40

[1] Q_{critical} estimated as 0.38 m^3/s (40% of the predeveloped two-year flow).

TABLE 2.

The Top Five Highest 1-h Rainfall Periods as Recorded by National Oceanic and Atmospheric Administration under the Pre- and Postretrofit Analysis Periods Show That Four of the Five Peak Intensities Were Larger during the Postretrofit Period, Which Is Consistent with the Larger Flow Depths That Were Measured during the Rarest Events at the Upstream Control Site during the Postretrofit Period (Figure 9, top left). In addition, the fewer days with precipitation and less total precipitation during the postretrofit period suggests that the retrofit device was the primary driver of the extended baseflows during the postretrofit period (Figure 9, middle right).

	Preretrofit	**Postretrofit**
Start date	March 7, 2013	December 22, 2013
End date	December 20, 2013	October 3, 2014
Top five 1-h rainfall periods (cm)		
Most intense	3.30	4.95
2nd	3.10	2.84
3rd	1.98	2.24
4th	1.73	2.11
5th	1.68	1.96
Total rainfall		
Days with precipitation ≥2.5 mm	103	99
Total precipitation (cm)	102.77	88.34

TABLE 3.

Order of Magnitude Unit Cost Estimates of Channel Protection Strategies Indicate that Detention Basin Retrofits Have the Potential to Be About 1-2 Orders of Magnitude Lower Than Construction of New BMPs, Including Distributed Green Infrastructure Practices, as well as In-Channel Stream Restoration Construction Measures.

Channel Protection Strategy	Approximate Cost (per km^2) of Drainage Area	Notes
Distributed green infrastructure	$7,300,000	Lowest cost alternative from King County (2013) pilot study with goals that included restoration of the flow regime and water quality in a previously developed but unmanaged neighborhood
In-channel stream restoration	$1,040,000	Stream restoration at ~$650 per m, converted to drainage area via N.KY drainage density of ~1.6 km/km^2 (Hawley *et al.* 2013b)
New detention basins	$715,000	Unit cost of a new surface storage basin designed for a previously developed (but unmanaged) watershed and optimized for channel protection from Hawley *et al.* (2012b)
Detention basin retrofits	$110,000	Detain H_2O technology ($10,000/unit installed) based on the 9.1 ha-drainage area to the pilot basin. Unit costs will vary by contributing drainage area (typically ~4-40 ha per basin)