



SD1's Regionally-Calibrated Hydromodification Program



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1.0 Executive Summary

Sanitation District No. 1 of Northern Kentucky (SD1) has been a leading utility in implementing channel protection considerations into storm water management, planning, and design. SD1's robust Hydromodification Monitoring Program has provided an invaluable foundation to understanding the issues of channel instability and developing regionally-calibrated storm water management strategies. Numerous studies have been completed across its three-county service area to document the extent and severity of hydromodification in Northern Kentucky, including impacts to stream stability, habitat, water quality, and biotic integrity, as well as adjacent property and infrastructure.

There are numerous examples of storm water design methodologies that have been used in other parts of the country to protect streams from excess erosion, and they range widely in terms of design complexity, effectiveness at protecting stream integrity, and cost. Rather than copy an approach from another region that may or may not be appropriate in Northern Kentucky, SD1 has used its hydrogeomorphic data to calibrate a channel protection approach that is specific to the needs of Northern Kentucky streams. In addition to flood control and water quality requirements already set by SD1, designing for the critical flow for bed material mobility, or $Q_{critical}$, has been analyzed to be appropriate for both new and redevelopment projects. On most development projects, where storm water controls manage runoff from less than 100 acres, the $Q_{critical}$ approach can be simplified to a level that requires no additional steps or modeling than what is currently required for developers. Design engineers simply revise the design target for one of the five flood control design storms that they are already required to evaluate. Furthermore, modeling efforts have confirmed that the size of storm water management facilities and associated costs are not expected to appreciably increase in most cases.

On larger development projects with areas draining more than 100 acres, as well as on storm water master planning projects, a more rigorous sediment transport modeling approach is optimal, commensurate with the more complex level of hydrologic/hydraulic modeling that is typically undertaken for large-scale projects. The sediment transport modeling approach is intended to reduce the risk of excess stream erosion and instability without requiring full-scale duration controls or hydrograph matching, proposed in other communities which are relatively impractical and costly in the Northern Kentucky setting.

SD1 has been involved with the implementation of several pilot projects to evaluate the feasibility and effectiveness of the $Q_{critical}$ approach across several settings and project types. One of the pilot installations involves retrofitting a detention basin outlet control structure and has been developed in association with partners including the United States Environmental Protection Agency Office of Research and Development (USEPA/ORD), Toyota, and Boone County Conservation District (BCCD). This patentable retrofit technology for existing detention basins has the potential to improve the performance of storm water assets that are already in the ground and could be 10- to 100-times more cost-effective at reducing stream erosion than building new storm water controls (Hawley *et al.*, 2013a).

Expanded implementation by SD1, other regional storm water managers (e.g., City of Florence and KYTC), watershed groups (e.g., Banklick, Gunpowder, and Woolper Creek Initiatives), property owners with existing detention basins, and developers will continue to demonstrate that Northern Kentucky has the ability to cost-effectively manage storm water in ways that improve stream stability, preserve aquatic health, protect property and infrastructure from stream erosion, and strive to achieve the goals of the Clean Water Act. SD1's approach to channel protection has been scientifically vetted, as

supported by the number of publications that have been published in peer reviewed journals as well as the numerous local, national, and international conferences where SD1 has been invited to present. This approach has been well-received by both SD1's utility peers as well as state and federal regulators, particularly in terms of the cost-conscience way that SD1 has advanced its innovative approach to hydromodification management.

2.0 Introduction

Hydromodification is the altering of a stream through channelization, dams, and/or streambank erosion due to changes in the flow regime, and the USEPA has listed this as one of the leading sources of impairments to waters across the United States. Although there are numerous types and causes of hydromodification, in urban and suburban areas, the term is generally linked to excess storm water runoff from impervious surfaces. The increasing amount of new impervious surfaces leads to both higher peak flows and longer durations of such erosive flows (Konrad and Booth, 2002; Hawley and Bledsoe, 2011). Civil engineers have long established that "if such increases are not minimized, the natural streams will enlarge their channels to accommodate the increased loads by scouring their banks and beds," (ASCE and WEF, 1992, p.49). Corresponding stream erosion not only creates water quality impacts, but can also cause property loss and damage to public/private infrastructure such as roads (Figure 1), sewers, and gas mains (Richey, 1982; Hawley *et al.*, 2013a). These impacts can also extend to aquatic life and habitat (Figure 2), which can be degraded by excessively erosive flows that create unnatural rates of disturbance, excess loads of fine sediment, and habitat embeddedness, among other factors (Walsh *et al.*, 2005; Poff *et al.*, 2006).



Figure 1. Hydromodification causes property loss and damage to public infrastructure, such as roads.



Figure 2. Inadequately managed storm water runoff in developed watersheds leads to degraded aquatic life and habitat in stream systems. This illustrates the difference between developed and undeveloped watersheds in Northern Kentucky. Owl Creek, depicted on the left, is 9% impervious and 3.7 mi². Middle Creek, depicted on the right is 0.6% impervious.

The 2004 *National Water Quality Inventory: Report to Congress* (USEPA, 2009) listed hydromodification as the second leading source of impairment in assessed rivers and streams. It also reports the top 10 causes of impairment, many of which are linked to hydromodification, including habitat alteration, impaired biota, nutrients, flow alteration, and turbidity. Within Kentucky, sedimentation/siltation, which includes total suspended solids (TSS), is the top ranked cause of impairment for streams (KDOW, 2010). Locally, detailed studies have been completed that demonstrate hydromodification is the dominant source of TSS within the urban and suburban watersheds (GCWI, In review).

Although the majority of states and communities have not begun to manage storm water in ways that explicitly combat the effects of hydromodification, some are incorporating channel protection policies into their rules and regulations. California considers hydromodification a serious storm water impairment and has required hydromodification management plans as a part of many Phase 1 and Phase 2 (MS4) permits (Stein *et al.*, 2012). Santa Clara, California (2004) requires post-development flow magnitudes and durations to match pre-development for everything between 10% of the 2-year peak flow and the 10-year peak flow. In developing the regulation, they found this to be where 90% of the erosive work in the channel is done. In San Diego County, California, designers are essentially required to match pre-development flow magnitudes and durations for all flows that have potential to erode the channel, with the exception of those that occur less frequently than every 10 years (San Diego, 2011).

In New York State (2010), a two-tiered approach is used, depending on the size and imperviousness of the project. For sites smaller than 50 acres or less than 25% impervious, the designer is asked to include 24-hour extended detention controls for the 1-year, 24-hour event. For areas larger than 50 acres or greater than 25% impervious, New York State (2010) suggests conducting a geomorphic survey of the downstream area, then using storm water controls to achieve channel stability. Maryland (2000), Vermont (2002), and Knox County (2008), Tennessee have similar requirements regarding installation of extended detention controls for the 1-year, 24-hour event under multiple assumptions that 1) the 1-year flow corresponds to the bankfull flow, and 2) the bankfull flow performs a large majority of the work on the channel boundary. In a recent review of such channel protection strategies, Hawley (2012) was not able to find any data analysis or monitoring that supported the assumptions noted above for the systems in question and noted that the presumptive focus on the 1-year storm ignores the fact that any flow that exceeds the critical flow for bed mobility has the potential to erode the channel. For this reason, the author predicted that the extended detention strategy could have a low to indeterminate level of effectiveness regarding protecting streams from excess erosion. Table 1 summarizes the Hawley (2012) findings.

Table 1. Summary of channel protection approaches in United States communities (Adapted from Hawley, 2012).

Channel Protection Approach	Corresponding Level of Stream Integrity	Example Communities
None	Low	> 95% of communities
Extended detention (of 1-yr storm)	Low – Unknown	NY State (2010) ^(a) , Maryland (2000), Vermont (2002), Knox County (2008)
Regionally-calibrated controls	Unknown – High	Santa Clara, CA (2004), San Diego County (2011)

^(a)New York State's (2010) Stormwater Management Design Manual recommends a tailored approach on projects affecting greater than 50 acres with more than 25% impervious area, based on a downstream geomorphic assessment. However, on sites less than 50 acres or less than 25% imperviousness, a broad-brushed approach of extended detention is recommended.

Although the approaches above may not be optimal for the Northern Kentucky setting, these states and cities have made contributions to understanding the issue of hydromodification across several regions of the United States, and many have taken efforts to incorporate channel protection controls into their storm water management policies. However, prior to 2008, there were no such programs in Northern Kentucky, nor the broader Outer Bluegrass Physiographic Region, or even the Commonwealth of Kentucky. Hydromodification had long been suspected to be a concern in Northern Kentucky, based on reports by field personnel, as well as private property owners, who noticed that streams along their property had incurred noticeable increases in flood magnitudes, frequencies, and erosion since development(s) had been built upstream. The relatively steep setting is also known for being a region with common geotechnical concerns, such as landslides, and stream downcutting as well as bank erosion that can directly increase the risk for such hillside slippages by increasing both hillside height and steepness. Given the risks that come with increased stream instability, as well as its impacts to stream integrity, it was in SD1's and the region's best interest to develop a better understanding of hydromodification in Northern Kentucky. Therefore, SD1 enlisted an independent expert to conduct preliminary field assessments. These initial assessments included approximately 50 sites from across the entire region, the results of which confirmed that there was a cause for concern of hydromodification in Northern Kentucky streams.

Since 2008, SD1 has made substantial progress in developing a hydromodification program to document the problem of channel instability and begin to develop and calibrate regionally-appropriate storm water management tools and solutions. More specifically, measurements of the extent and severity of impacts from hydromodification in Northern Kentucky have been gathered via SD1's Hydromodification Monitoring Program, a quantitative assessment program that includes detailed hydrogeomorphic data collection across three distinct dimensions of stream geomorphology. This data has provided an empirical foundation for developing locally-calibrated management approaches to mitigate hydromodification in Northern Kentucky, including the development of regional estimates of the critical flow for stream channel protection. Several pilot projects are underway to assess the performance of these management approaches and adapt the program as necessary.

It is important to stress that the program has been developed on an extremely efficient budget. SD1 reduced the reliance on outside consultants by collecting data with in-house staff. Additionally, SD1 has collaborated and partnered on numerous opportunities with outside funding sources, such as United States Environmental Protection Agency Office of Research and Development (USEPA/ORD), Kentucky Division of Water (KDOW), Boone County Conservation District (BCCD), Banklick Watershed Council, Licking River Watershed Watch, Northern Kentucky University Center for Environmental Restoration (NKU CER), and Thomas More College. This has allowed SD1 to reduce costs, utilize local expertise, and provide educational opportunities.

3.0 Extent/Severity of Hydromodification and Related Impacts in Northern Kentucky

Urbanization directly impacts the quality, volume, and efficiency of the process in which precipitation is converted to storm water runoff, and ultimately stream flow. These changes to the hydrologic cycle create corresponding impacts in receiving streams, including channel erosion, biologic degradation, water quality impairments, damaged infrastructure and loss of property (ASCE and WEF, 1992; Walsh *et al.*, 2005; Hawley *et al.*, 2013a). From SD1's Hydromodification Monitoring Program to watershed plans, several actions have already been taken by SD1 and other Northern Kentucky entities to understand the extent and severity of hydromodification and its related impacts. In addition to SD1's robust monitoring

program, both the Gunpowder Creek and Woolper Creek Watershed Initiatives were centered on the issue of hydromodification and include valuable data regarding the condition of Northern Kentucky streams.

3.1 Hydromodification Monitoring Program - Detailed Data Collection

Understanding existing conditions provides insights that guide proper storm water management to protect, preserve, and restore stream systems, public infrastructure, and biologic integrity. Therefore, in 2008 SD1 began to collect detailed hydrogeomorphic surveying data (Figure 3) as part of its Hydromodification Monitoring Program. This robust dataset has provided quantitative information to document channel instability, understand the scale of the problem and its relationship to watershed development, and ultimately develop more holistic storm water management solutions that consider channel protection. Over the last several years and in partnership with numerous efforts, (e.g., BCCD's Gunpowder and Woolper Creek Watershed Initiatives), SD1 has compiled a hydrogeomorphic database that includes surveys at approximately 60 stream sites within its three-county service area that covers approximately 1,500 miles of streams. Data collection includes repeated measurements of channel cross-sectional form, longitudinal profile, and bed material composition using industry standard procedures (Harrelson *et al.*, 1994; Bunte and Abt, 2001). The database and methodology is comparable to other large regional efforts, such as the peer-reviewed program developed for the six-county area of Southern California that includes over 80 sites and has since been used in numerous publications (e.g. Hawley, 2009; Bledsoe *et al.*, 2012) that have informed regional storm water policy (e.g. San Diego, 2011).



Figure 3. Collecting hydrogeomorphic survey data throughout Northern Kentucky

From 2008 to 2010, a detailed geomorphic study was conducted across 40 sites throughout SD1's service area. SD1 conducted annual geomorphic surveys at each of these monitoring locations, with the objective of documenting average rates of change in channel cross section, profile, and bed material composition (Hawley *et al.*, 2013b). The results of the peer-reviewed study substantiate that urbanization is associated with channel enlargement, shorter riffles, longer/deeper pools (Figure 4), and coarser/more homogenous bed material. The study also showed that headcutting was a dominant mechanism for urban channels in Northern Kentucky, as streams tended to flatten their slope in an attempt to decrease the erosive power of the urban flow regime. In many cases, these slope adjustments pivoted around a downstream hardpoint, such as bedrock or exposed urban infrastructure, similar to the discontinuous channel evolution trajectories observed by researchers in other settings (Chin and Gregory, 2001; Hawley *et al.*, 2012a; Hawley and Bledsoe, 2013). Several useful inferences have been made from this original study in Northern Kentucky, which have since been corroborated by data collection at independent sites as a part of the Gunpowder and Woolper Creek Watershed Initiatives (GCWI, In review; WCWI, In prep). The initial response of Northern Kentucky streams seems to be increased bed material transport, which tends to gradually coarsen the streambed and create a more homogenous habitat. This corresponds to profile instability, headcut trajectories, and a gradual flattening of channel slope, which inherently results in longer pool habitats at the expense of riffle habitat. As stream downcutting continues, this ultimately makes the banks taller and more prone to geotechnical mass wasting failure, which can be a dominant source of fine sediment loads (GCWI, In review) and can exacerbate property loss and damaged infrastructure.

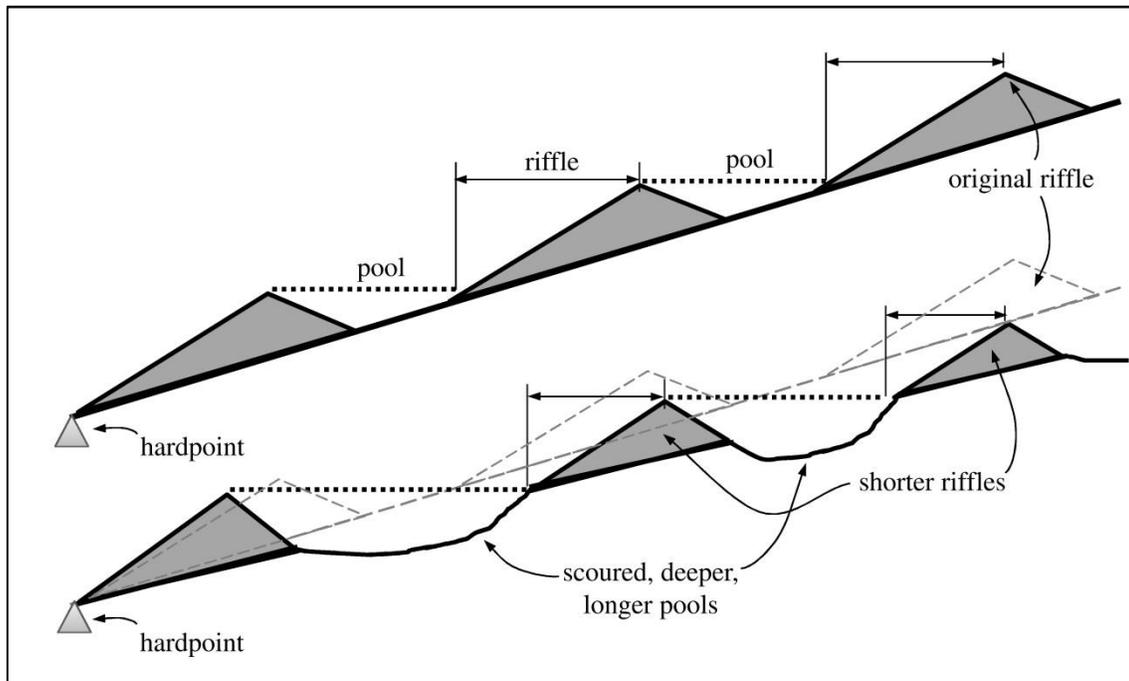


Figure 4. Shortening of riffles and deepening and lengthening of pools verified by Northern Kentucky field data (Hawley et al., 2013b).

These findings helped to underscore the mechanisms and sequences of urban stream degradation, as well as evaluate appropriate strategies for stream restoration. For example, in streams where urban instability is just beginning, storm water controls could be implemented to restore the system before the network has flushed too much of its habitat-forming bed material downstream. In contrast, in systems that have been heavily urbanized for several decades and have flushed most of their cobble/gravel bed material downstream, restoration activities may require a reintroduction of habitat-forming particles in addition to storm water controls aimed at reducing the erosive power of the flow regime.

3.2 Northern Kentucky's Hydromodification Extents Measured by a Regionally-calibrated Stability Index

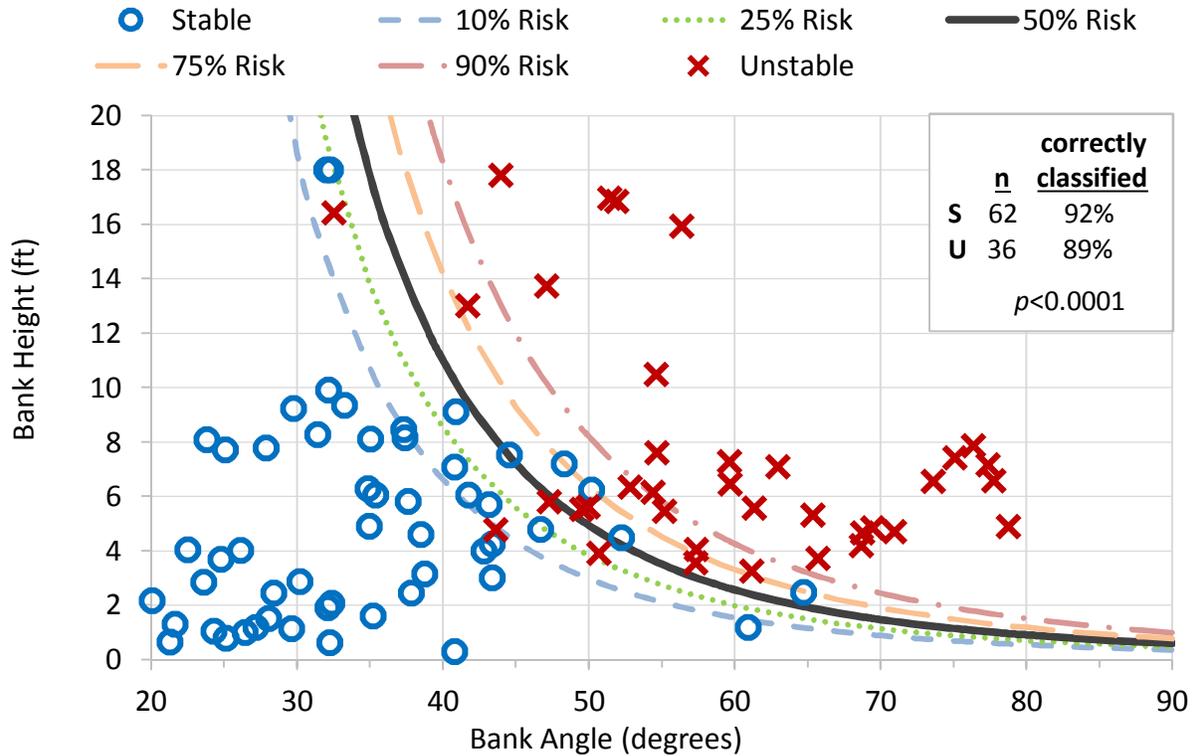
SD1's detailed hydrogeomorphic survey data served as the basis for the development of a stream stability index specifically for the Northern Kentucky region. This index is a rapid field assessment tool that characterizes the overall stability condition of the stream, requiring approximately 15 minutes to conduct. The index includes seven parameters that are designed to represent cross-sectional, profile, and bed material stability, consistent with the dimensions that are captured by SD1's Hydromodification Monitoring Program. The overall score, based on a scale of 0 to 10, with 0 being the most unstable and 10 being the most stable, has been incorporated into SD1's overall Stream Condition Index (SCI) (LTI, 2013). The equation for the stability index is as follows (Sustainable Streams, 2012a):

$$SD1 = -8.5 + 0.15 * LB + 0.15 * RB + 0.3 * Shape + 0.15 * Bedrock + 0.25 * Embeddedness + 0.25 * Pool Depth + 0.25 * Riffle Freq.$$

Where:

- LB = Left Bank Score
- RB = Right Bank Score
- Shape = Shape Score
- Bedrock = Bedrock Score
- Embeddedness = Embeddedness Score
- Pool Depth = Pool Depth Score
- Riffle Freq. = Riffle Frequency Score

Although other stability assessment methods exist, such as Rosgen's (1996; 2001) BEHI protocol, the SD1 index has numerous advantages for Northern Kentucky streams. First, it was calibrated with Northern Kentucky stream data as opposed to streams from other settings, such as the forested streams in Colorado and Wyoming that were used to calibrate BEHI. Second, the SD1 index considers the combination of bank height and angle when assessing bank stability, as opposed to height and angle in separate categories, which is the case with the BEHI approach. As seen in Figure 5, the risk of geomorphological mass wasting bank failure for a given bank angle changes with bank height (e.g., 45 degrees is likely to be stable at three feet but not at ten feet), just as failure for a given bank height changes with angle (e.g., a six foot bank is likely to be stable at 40 degrees but not at 60 degrees). Third, the SD1 index incorporates parameters that are specifically calibrated to represent stream profile and bed material stability as opposed to an exclusive focus on cross-sectional and bank stability. The bedrock and embeddedness parameters were statistically related to measures of bed material stability, and the pool depth and riffle frequency parameters were correlated with profile stability. Because biotic health depends on these aspects of stream stability in addition to bank stability, the SD1 stability index is a more holistic measure of geomorphic condition as it relates to other components of the stream assessment program.



Logistic Regression thresholds ($p < 0.0001$) developed for stable vs. unstable banks with failure dominated by mass wasting, withholding bedrock banks and unstable banks dominated by fluvial failure.

Figure 5. Risk of geotechnical bank failure by mass wasting is a function of both bank height and angle.

Between 2012 and 2013, SD1 used this rapid assessment tool to measure stream stability at 67 sites across the Northern Kentucky region (Figure 6 presents an example site in the Dry Creek Watershed). These data informed a performance evaluation of the stream stability index that validated it using measured rates of instability from sites that were independent from the sites used during the index calibration (Sustainable Streams, 2013a). Figure 7 presents the distribution of these scores, with most of the stream sites scoring in the very poor, poor, and fair categories (i.e., scores ranging from one to six). Only 11% of all the stability indices scored equal to or greater than a seven, illustrating that few Northern Kentucky streams are still in relatively good condition (i.e., least impacted). This has adverse impacts for aquatic life because, as demonstrated in the validation memo, titled Validation of Regionally-calibrated Channel Stability Index for Northern Kentucky Streams (Sustainable Streams, 2013a), biologic measures associated with good integrity (e.g., MBI and m%EPT) tend to be positively associated with stream stability, whereas measures associated with poor biotic integrity (e.g., %Chir&%OI) tend to be associated with stream instability.



Figure 6. Severely eroded streambank in the Dry Creek Watershed is at greater than 90% risk of geotechnical failure.

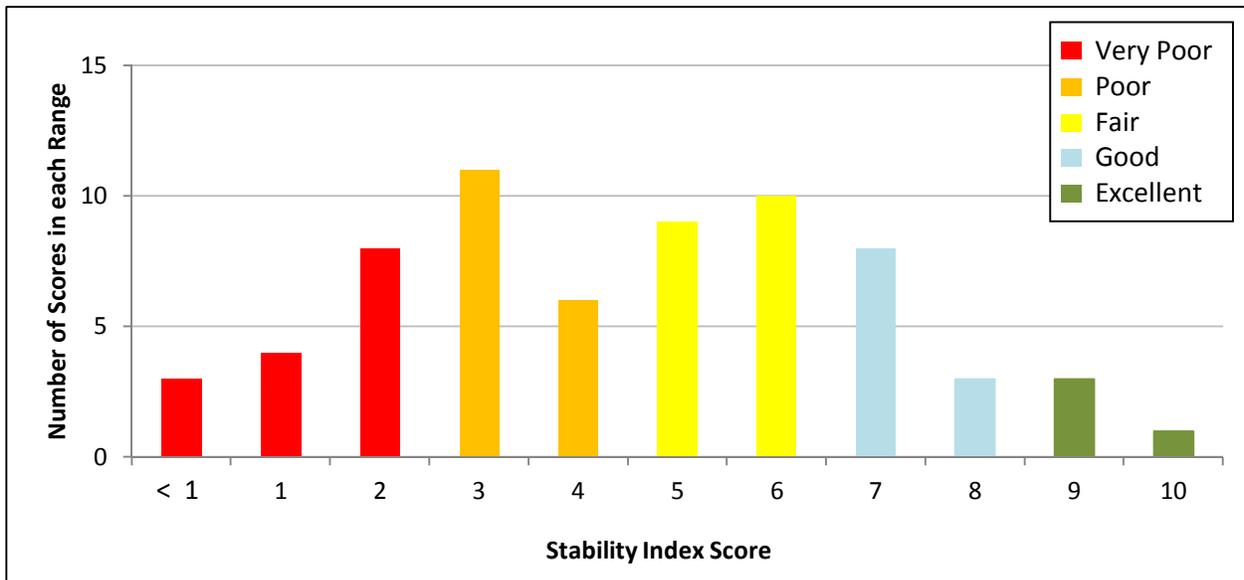


Figure 7. Distribution of stability index scores measured in 2012 and 2013.

As mentioned above, this stability assessment tool is one component of the overall SCI, represented by the lower left quadrant of the square depicted in Figure 8. This figure presents an example of the SCI scores for the Dry Creek Watershed from 2008. The stream reaches in Dry Creek are some of SD1's most unstable channels, whereas the water chemistry in the stream network tends to be fair. Because biological health depends on both stability and water quality, the Dry Creek case study implies that, even with investments to reduce water pollution, overall stream integrity would not be expected to fully recover without also improving stream stability. The SCI analysis of Dry Creek indicates that channel stability is one of the primary drivers of the poor/fair biological communities throughout the network.

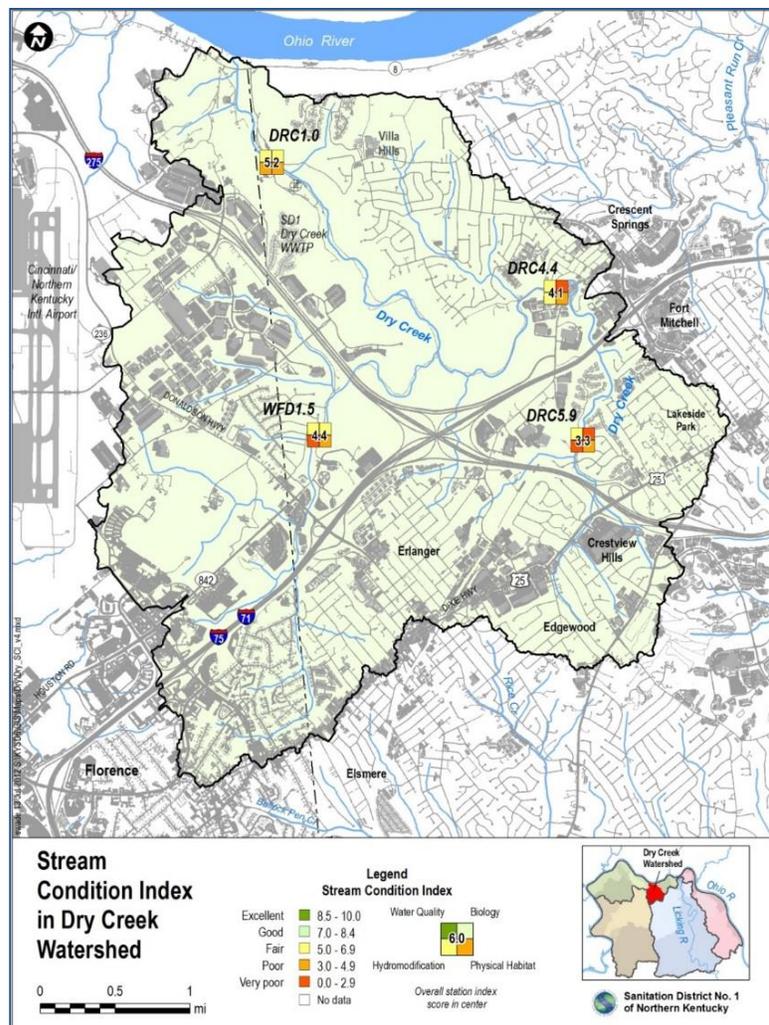


Figure 8. Stream Condition Index in Dry Creek Watershed.

3.3 Stream Integrity Impacts

Stream integrity is rooted in the hydrology of the watershed (Poff *et al.*, 1997), and alteration of the landscape, particularly through the addition of impervious surfaces, can dramatically change the flow regime and degrade the overall integrity of the stream. Aquatic life depends on the natural flow regime for habitat stability and water quality. The more erosive and unstable stream flows associated with inadequately managed impervious surfaces can create unstable habitat, causing physical disturbance, such as bank and bed erosion, directly impacting life cycles of aquatic insects and fish. The stream function pyramid (Figure 9) can serve as a conceptual visualization of how hydromodification can impact stream integrity through both direct and indirect pathways.

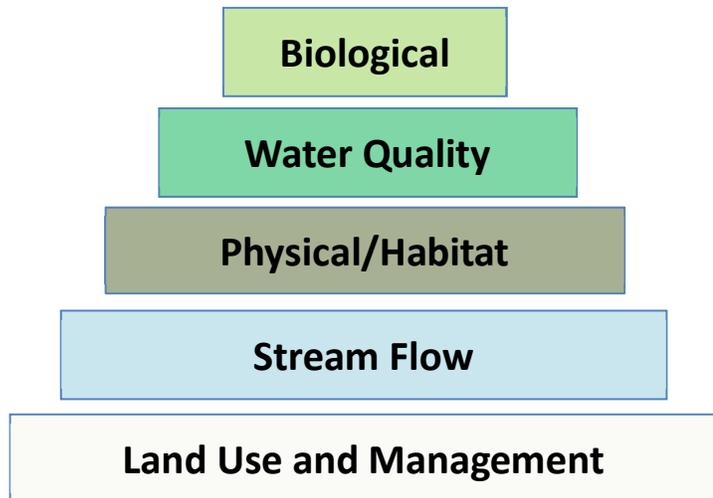


Figure 9. Stream function pyramid (Adapted from Harmon *et al.* (2012)).

Three detailed case studies in the Gunpowder Creek, Woolper Creek, and Middle Creek watersheds further underscore the various impacts of hydromodification to Northern Kentucky stream networks. The Gunpowder Creek Watershed Initiative (GCWI) and Woolper Creek Watershed Initiative (WCWI) are working to develop watershed plans using a suite of monitoring data from each watershed, both of which are in Boone County, Kentucky. These streams have segments that are listed as impaired waterways by KDOW (2010), with the three most prominent water quality concerns being sediment, bacteria, and nutrients. By contrast, the third case study, in the Middle Creek Watershed (also in Boone County) serves as reference site for SD1's monitoring program because of the high quality biologic integrity of this stream.

3.3a Case Study #1: Gunpowder Creek Watershed

The results of the Gunpowder Creek Watershed Plan have identified sediment as the largest water quality concern, with TSS loads ~30 to 60 times benchmark levels in the two most developed headwater stream segments. Multiple years of geometric stream surveys have documented that streambank erosion is a primary source of sediment pollution (Figure 10), with measured rates of erosion that could explain more than 100% of the sediment load measured in the water column at most of the monitoring locations within developed subwatersheds (GCWI, In review). That is, so much sediment could be coming off of the banks that the stream is not able to move it all through the system, resulting in sedimentation and habitat embeddedness. Poor habitat and degraded biological communities were also associated with the developed subwatersheds within the Gunpowder Creek stream



Figure 10. Tension crack along the streambank in South Fork Gunpowder is the primary source of sediment pollution

network. Overall, the monitoring data presented in this Watershed Plan illustrates how urbanization and inadequate management of storm water runoff from impervious surfaces causes erosive flows in the receiving stream, which results in stream instability, bank erosion, habitat degradation, and water quality impacts, all of which have adverse effects on aquatic life.

3.3b Case Study #2: Woolper Creek Watershed

Analysis of the monitoring data at 18 sites with annually-repeated hydromodification surveys in the Woolper Creek Watershed illustrates that the most unstable hydromodification monitoring sites also scored the lowest on the Habitat Assessments, indicating that the physical integrity of the stream strongly impacts habitat conditions (WCWI, In prep). In contrast to the Gunpowder Creek case study, however, the Woolper Creek data documented relatively good water quality throughout the stream network, with constituent levels that were at or near KDOW's benchmark levels. These data imply that the fair biological communities observed at the most developed headwater sites in the Woolper Creek Watershed were not impacted by poor water quality, but rather, by the unstable streambeds that have likely impacted aquatic communities directly through immediate disturbance and indirectly via habitat degradation.



Figure 11. Mobilized rock in the Upper Woolper Creek Subwatershed

As discussed above (Section 3.1), excess disturbance of the streambed tends to be one of the initial responses of Northern Kentucky streams as their watersheds become developed. Because the Woolper Creek Watershed has only recently started to become developed, the streams are still undergoing the initial phases of instability, which explains why their beds were some of the most unstable that have ever been measured in all of Northern Kentucky, but their banks have not yet become chronically unstable (Figure 11). In contrast, the Gunpowder Creek Watershed has been developed for a much longer period of time and has higher amounts of impervious surface (e.g., the Woolper Creek Watershed is approximately 25% developed while the Gunpowder Creek Watershed is close to 50% developed (LTI, 2009a; LTI, 2009b)). Most of the developed monitoring sites in the Gunpowder Creek Watershed have already coarsened their beds to the point of being dominated by exposed bedrock, leaving very little habitat for aquatic organisms. The banks have become taller and steeper and tend to be experiencing extensive failure by mass wasting, which corresponds to overall channel widening and enlargement as well as poor water quality due to the excess loads of fine sediment.

3.3c Case Study #3: Middle Creek Watershed

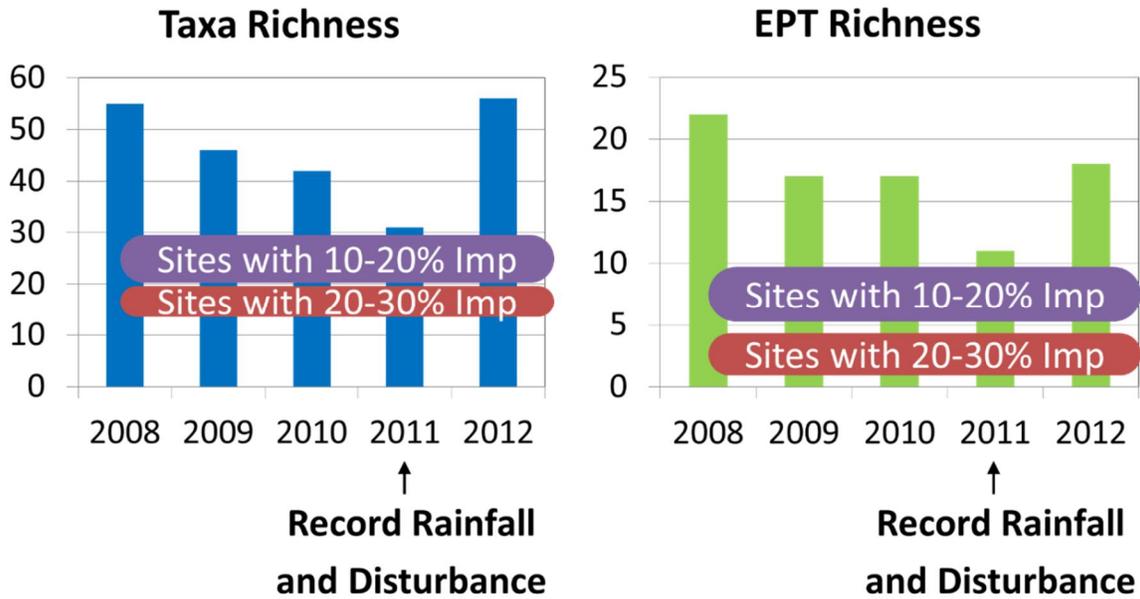
A third example of impacts to stream system integrity in Northern Kentucky includes a case study of Middle Creek, a least disturbed stream that has been used as a reference stream since SD1's monitoring began in 2008 (Figure 12). In 2011, the Northern Kentucky area experienced record rainfall, which provided a unique opportunity to evaluate the impact and recovery from excessively erosive flows in a reference watershed. For this case study, the record rainfall in 2011 served as an analog for the erosive flows that would be caused by urbanization. However, because the habitat and biology are



Figure 12. Middle Creek is an SD1 reference site.

of high quality (i.e., high biodiversity) in Middle Creek, any impacts to biological health can be directly inferred by the erosive flows as opposed to the degraded habitat and poor water quality that are typically associated with urban streams (e.g., the Woolper and Gunpowder case studies discussed above). Using hydrogeomorphic survey data between 2008 and 2012, statistically-significant geomorphic instability was associated with the exceptionally erosive flows from the record rainfall year of 2011 (Hawley *et al.*, 2013d). Biological health also showed a clear impact during the 2011 year of high geomorphic disturbance, but recovered during the following year when rainfall conditions were more typical (Reference the dip in the vertical bars in 2011 and recovery in 2012 in Figure 13). The study documents the resilience of nature when the system as a whole remains intact—indeed, taxa richness was the highest ever recorded in 2012, indicating that natural frequencies of disturbance may play an important role in maintaining diverse communities in regional streams.

However, similar to a forest immediately after a fire, the first taxa to recolonize following a major streambed disturbance tend to be the fast-growing species (i.e., “weedy” species). If a stream is disturbed too frequently, the longer-lived species are not able to recover and biological communities tend to be dominated by these fast-growing species at the expense of sensitive species such as EPTs (*Ephemeroptera*, *Plecoptera*, and *Trichoptera*; i.e., mayflies, stoneflies, and caddisflies), which are often considered as taxa that are emblematic of good water quality. The Middle Creek case study documents that partially developed watersheds (e.g., 10-20% impervious, represented by the purple bars in Figure 13) may have limited taxa richness, especially EPT taxa, because of unnatural frequencies of disturbance even if the water quality was otherwise sufficient for aquatic life. The taxa richness at sites with 10-20% imperviousness ranges from 20-30 and it ranges from 15-20 at sites that are 20-30% impervious. The similarity of the taxa and EPT richness of Middle Creek in 2011 to the partially-developed watersheds explains why unnatural frequencies of disturbance caused the maximum richness levels for partially-developed watersheds to coincide with the 2011 levels in Middle Creek (Reference year 2011 in Figure 13). Streambed disturbance alone, if it becomes too frequent, can substantially impact a stream's biologic potential, even if storm water and land use practices were in place to sufficiently protect habitat and water quality (Walsh *et al.*, 2005).



3.3d Case Study Summary

These case studies further underscore the mechanisms by which hydromodification impacts geomorphic stability, habitat, water quality, and biologic integrity (Figure 14). Both direct and indirect impacts to stream integrity begin with excess disturbance of the streambed material, caused by storm water management approaches that do not adequately maintain the magnitude or frequency of the natural disturbance regime. If the natural frequency is maintained, biologic integrity can recover and even thrive following the occasional period of streambed erosion (e.g., Middle Creek). If, however, the disturbance regime becomes excessive, biological communities are immediately impacted (e.g., Woolper), and cycles of habitat degradation, bank erosion, water quality impacts, and widening ensue (e.g., Gunpowder). These sequences of channel instability not only impact water quality and biology, but can also impact adjacent property and infrastructure as discussed below.



Figure 14. Summary of Gunpowder, Woolper, and Middle Creek case studies.

3.4 Infrastructure and Property Impacts

Hydromodification can be damaging to stream integrity, as well as adjacent infrastructure and property. Inadequate management of storm water runoff accelerates stream instability, back erosion, and channel enlargement. As streams become wider and deeper they encounter adjacent and/or buried infrastructure, such as roads, sewers, and gas lines, all of which can be costly to repair (Figure 15). In 2011 alone, the Kentucky Transportation Cabinet (KYTC) had \$3.1 million in estimated damages to state-funded roads in Boone County that were attributable to flooding and channel instability. This scales to ~\$25,000 to \$50,000 per square mile per year in estimated damages to roadways (Hawley *et al.*, 2013a). Furthermore, SD1 recently spent more than \$500,000 to repair two locations of a trunk line along Banklick Creek that had been exposed and broken, and Duke Energy has spent approximately \$250,000 on stabilization efforts and repair/replacement costs of an overhead electric line and three gas main crossings in the Dry Creek corridor. Extrapolating these expenditures for the developed watersheds of Northern Kentucky results in ~\$2,500 per square mile per year in estimated damages to sewers and ~\$1,000 per square mile per year in estimated damages to gas and electric utilities, although relocation costs could be much more expensive (Hawley *et al.*, 2013a).

Costs may even be higher in select areas; for example, a recent study in the 12-square mile Dry Creek Watershed indicates that over \$2.3 million has been spent on recent infrastructure repairs and stream stabilization. The case study also documented over \$7 million worth of SD1 and roadway assets located within an "Extreme Risk Zone," which is defined as all stream crossings and infrastructure located within a 50-foot offset from the centerline of the main stem (Sustainable Streams and Strand, 2014). Figure 16 illustrates one of SD1's at-risk assets in the Dry Creek Watershed, the Dry Creek Wastewater Treatment Plant (WWTP), which is valued at over \$100 million. As evident by this photo, portions of the WWTP are located in the "High Risk Zone" (i.e., within a 100-foot buffer of the centerline of the stream) and almost half of the plant is located in the "Moderate Risk Zone" (i.e., within a 200-foot buffer of the centerline of the stream).

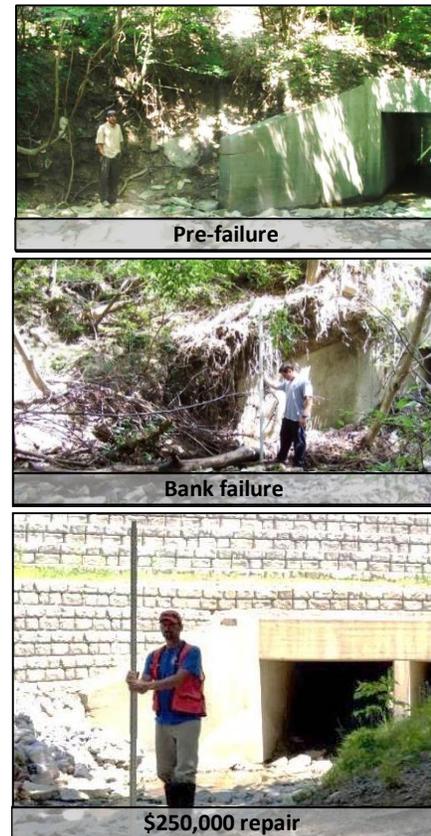


Figure 15. An example of infrastructure impacts. It cost \$250,000 to repair this culvert.

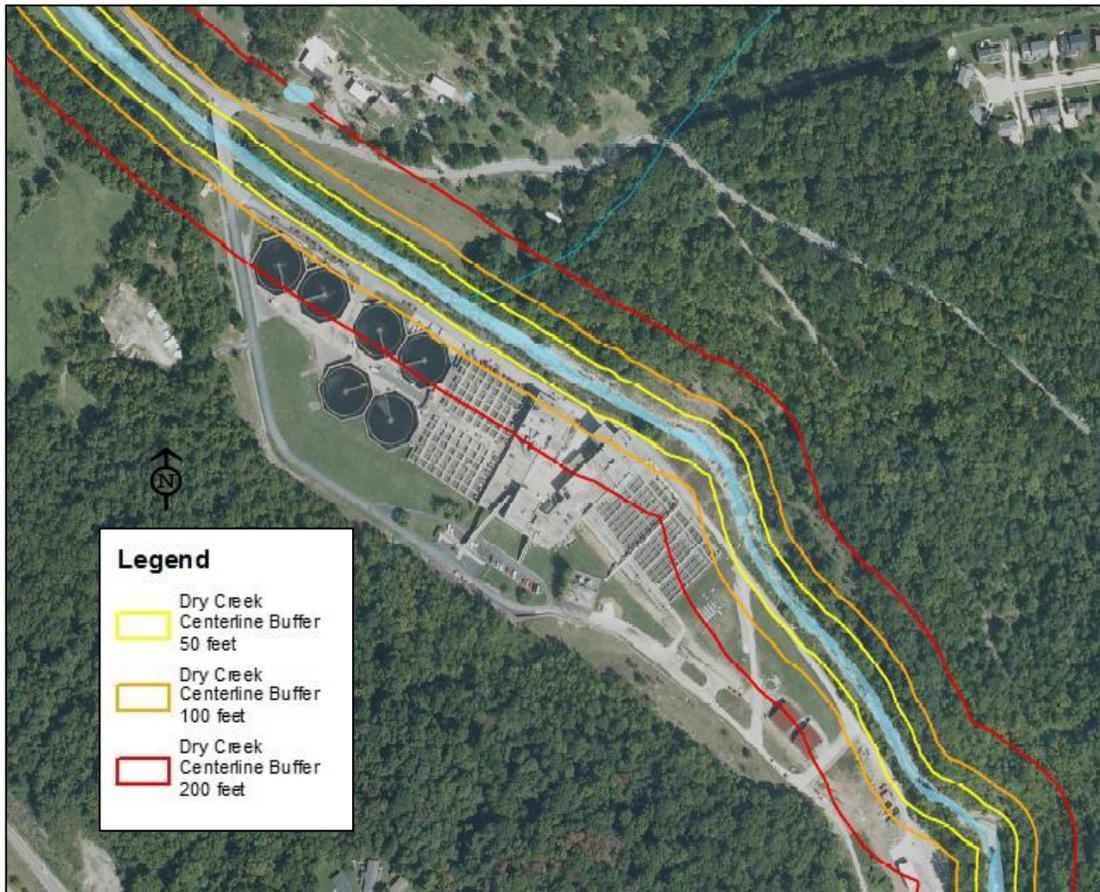


Figure 16. Proximity of \$100 million Dry Creek WWTP to unstable Dry Creek channel.

Private property is also impacted by hydromodification, and there have been numerous residents who have qualitatively documented higher rates of flooding and stream erosion associated with the conversion of upstream land from undeveloped to developed. Examples are abundant; however, a stream with a particularly high number of long-time residents documenting flooding problems is the South Fork of Gunpowder Creek, one of the most developed suburban watersheds in Northern Kentucky (Figure 17). The drainage area upstream of this location is approximately 40% impervious. Furthermore, the anecdotal evidence of stream enlargement, deepening, and widening by various long-time property owners is also supported by SD1's monitoring program discussed above (Section 3.1), which has quantitatively documented that streams draining undeveloped watersheds tend to be smaller than those that have been developed (Hawley *et al.*, 2013b).



Figure 17. Flooding along the South Fork of Gunpowder Creek, which is one of the most developed watersheds in Northern Kentucky (Photo courtesy of Alen Streutker, a resident along South Fork).

4.0 Determining Appropriate Storm Water Management Approaches for Northern Kentucky

"If a natural [stream] channel is to be used for carrying storm runoff from an urbanized area, it may be assumed initially that the changed runoff regime will result in erosion. Careful hydraulic analyses must be made of natural channels to evaluate these tendencies," (ASCE and WEF, 1992, p.280). Over 20 years ago engineers and scientists acknowledged that urban storm water management systems alter the runoff regime and that detailed analysis is necessary to protect the integrity of local community resources. However, channel protection and analysis of the urban flow regime has not been considered a priority until more recent years, as many communities throughout the United States are just now beginning to incorporate channel protection controls into their rules and regulations.

4.1 Northern Kentucky Storm Water Management History and Regulations

Conventional storm water management practices were not implemented when many of the older neighborhoods of Northern Kentucky were developed. There are several examples of areas throughout the region (i.e., Vernon Lane and Pleasant Run neighborhoods, see section 5.1a) that lack storm water controls other than traditional conveyance controls (e.g., pipes and ditches) that route water away from the area and to the nearest downstream open channel. It was quickly realized that these traditional conveyance controls were insufficient at managing the storm water and were creating flooding issues in downstream areas. As the need for storm water management became apparent, early storm water management efforts were implemented in portions of developed watersheds, such as the Horse Branch Creek Watershed, but the storm water controls have been insufficient at protecting stream stability. The resulting stream instability not only impacts SD1 infrastructure, but also puts Northern Kentucky's highways at risk (e.g., Interstate-275, Figure 18).



Figure 18. Exposed manhole and at risk roadway along the I-275 corridor in the Horse Branch Watershed.

As apparent in the examples discussed above, storm water management has evolved in Northern Kentucky, but is still inadequate at protecting streams and adjacent infrastructure from excess erosion. Detention requirements for the region were initiated in the mid-1990s, but differed among municipalities throughout the region. For SD1, the initial evolution of the regional storm water management program was primarily driven by USEPA and KDOW regulations. In 2003, the Northern Kentucky Regional Storm Water Management Program was developed to comply with the Phase II Storm Water Regulations of the Clean Water Act. As the newly formed regional storm water utility, SD1 created consistent storm water rules and regulations that were intended to address flood control (i.e., pre = post peak flow rates) across the region. Similar to many other storm water rules and regulations across the United States, SD1 enforces flood control policies that require developers to install storm water controls that match peak flows for set recurrence intervals, called peak matching. Although this methodology is common, it can be insufficient at controlling peak flows in the stream because hydrographs can have prolonged durations that combine to increase flood depths and erosive flows downstream (Figure 19; Atlanta Regional Commission, 2001).

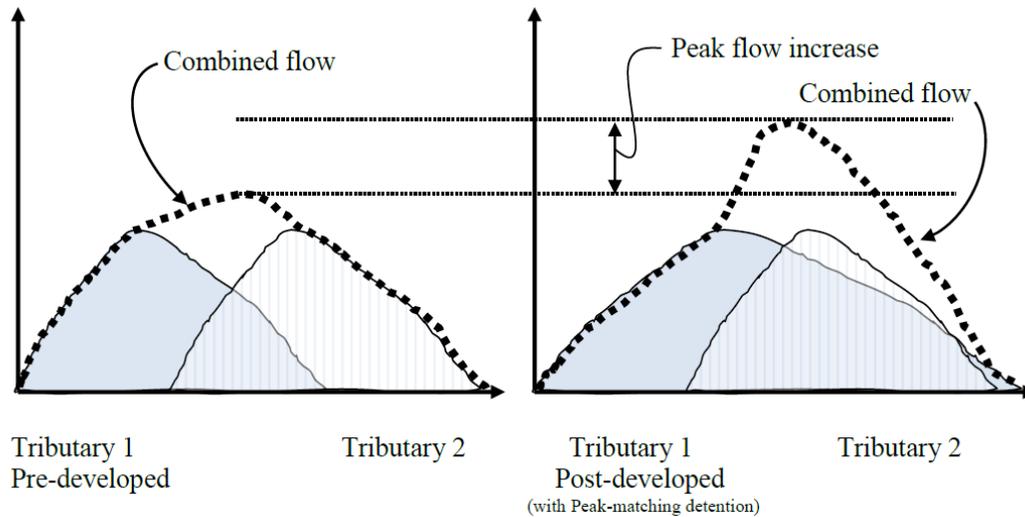


Figure 19. Effect of peak matching (Adapted from Georgia Stormwater Management Manual (Atlanta Regional Commission, 2001), Redrawn by Hawley (2012)).

The net effect of the peak matching strategy has resulted in impacts to stream integrity as well as public and private property. As identified earlier, in many cases sanitary sewers, highways, and other related infrastructure have been impacted by stream instability. SD1 storm water managers recognized the ineffectiveness of current methodologies to protect nearby utilities, private property and stream integrity due to excess stream erosion; and therefore, in 2008 SD1 initiated stream hydromodification studies in order to better understand the mechanisms causing stream degradation and provide the data needed to develop appropriate management strategies. Using this information SD1 currently promotes channel protection measures through educational outreach and credit policies that are intended to ensure that the post-developed flow regime results in the same or less erosion than would have occurred under pre-developed conditions (the details of which are described further in the sections below).

In 2011, KDOW's Phase II MS4 permit required SD1 to implement a water quality standard in addition to conventional flood control regulations. SD1 and the City of Florence's *Storm Water Best Management Practices (BMP) Manual* (2012) provides guidance on sizing storm water controls for the water quality volume. Locally, that equates to the first 0.8 inches of rainfall. Analyses have indicated that sizing controls for this volume will generally result in less erosive flows when compared to peak matching. However, sizing only for this volume will not optimize BMPs to adequately protect streams from excess erosion relative to the pre-developed setting (Sustainable Streams, 2012b).

This indicates that SD1's current storm water management policies, which focus on only water quality and flood control, are a step towards improving stream quality relative to the conventional peak matching strategy. However, they do not ensure that investments are made in a way that maintains or improves long-term channel stability because: 1) channel erosion typically begins in Northern Kentucky streams at a flow that is less than the 2-year design storm (i.e., ~3 inches in Figure 20) and regional flood controls are unlikely to have a sufficiently attenuating effect for flows less than the 2-year design storm (i.e., 97-99% of the precipitation volume in a typical year (Emerson *et al.*, 2003; Hawley, 2012), and 2) the prolonged durations of erosive flows exacerbate channel erosion even if flood peaks are maintained to pre-developed levels.

As mentioned previously in the Introduction (Section 2.0), there are several methodologies to design storm water controls for channel protection. Using channel protection methodologies developed in New York, an analysis was completed to better understand optimization of post-construction controls in the Northern Kentucky region. This analysis, shown in Table 2, highlights two modeled alternatives for attempting to retain 1 inch of rainfall on a 1-acre site with native soil infiltration rates and 50% impervious using bioretention. It is clear that both situations are impractical; 29 days is too long to draw down one event, and it is not feasible to put bioretention on 92% of a site when 50% of it is impervious (SD1, 2012; 2013).

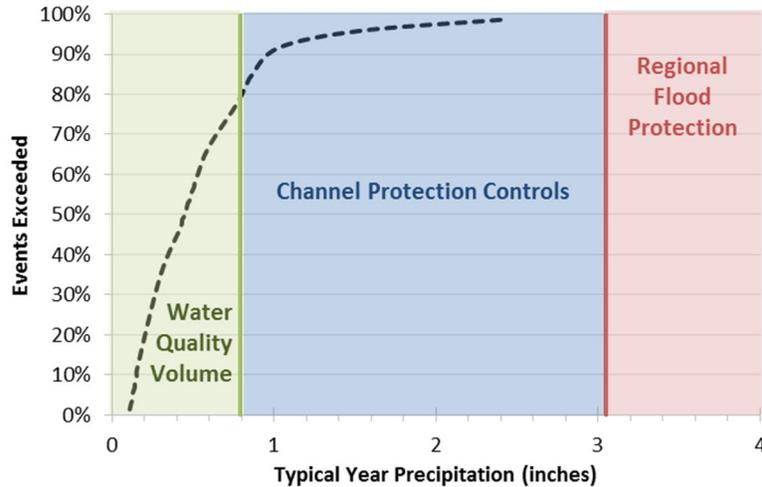


Figure 20. Typical year rainfall and recurrence probabilities for Northern Kentucky.

Table 2. Modeling results highlighting post-construction storm water controls assuming 1-inch retention requirement (SD1, 2012; 2013).

Infiltration Rate <i>in/hr</i>	Bioretention Facility Footprint		Drawdown Time <i>days</i>
	<i>SF</i>	<i>% of DA</i>	
0.001	2,900	7%	28.7
0.001	40,000	92%	4.0

Another alternative is to manage storm water for the critical flow for stream channel protection, or $Q_{critical}$, defined as the flow at which sediment transport begins, causing channel erosion, downcutting, widening, and overall instability. Northern Kentucky’s $Q_{critical}$ ranges from 40 to 50% of the 2-year peak flow (Q_2), as calculated by the regional equation for rural watersheds (Sustainable Streams, 2012b). This value was estimated using hydrogeomorphic survey data from 23 regional streams as well as industry standard mobility equations. Furthermore, this range was validated through analysis of USGS gage data at five of the hydromodification monitoring sites in close proximity to a gage. This analysis indicated that channel enlargement in cross-sectional area was positively correlated to the duration of gaged flows that exceeded the $Q_{critical}$ estimation of 40% of Q_2 (Sustainable Streams, 2012c; 2013b).

4.2 Storm Water Management for Channel Stability in Northern Kentucky

To manage storm water in a way that maintains or improves channel stability, relative to pre-developed conditions (promoting long-term stability), the cumulative erosive power of the post-developed flow regime must be equal to or less than that of the pre-developed flow regime. A theoretical approach to achieve this goal is to design storm water controls for hydrograph matching, such that the entire hydrograph for every storm is perfectly matched to the pre-developed hydrograph. However, the approach has limitations in terms of implementation. To implement such a policy, a community could

require duration controls in which models of long-term (e.g., 50 years) continuous rainfall simulations demonstrate that the cumulative durations of all flow magnitudes do not depart from the cumulative durations of the pre-developed scenario by an acceptable amount, such as 10%. This approach is impractical for the Northern Kentucky region, as it typically requires an excessive volume of necessary storage or the ability to infiltrate into the native soil. Providing large storage volumes can greatly increase construction costs, and the majority of Northern Kentucky's soils are not conducive to infiltrating storm water due to a high clay content. Therefore, the hydrograph matching approach has proven to be burdensome and costly in the Northern Kentucky region.

A more pragmatic way to design storm water controls, which is a less onerous alternative to hydrograph matching, is to focus only on the flows that actually erode the channel. That is, all streams have some capacity to resist erosion, and flows that do not exceed the force required to erode the bed or bank do not create channel instability. Because excess storm water volume that is released below $Q_{critical}$ does not create channel erosion, controls for those flows are unnecessary. Therefore, only the excess durations of flow magnitudes greater than $Q_{critical}$ matter because these flows transport the bed material and perform work on the channel boundary.

The key to long-term channel stability for Northern Kentucky streams is managing storm water such that the long-term cumulative erosion done by all flows greater than $Q_{critical}$ matches the cumulative erosion of the pre-developed setting. If this strategy is achieved on a watershed-scale, it would increase the likelihood that no erosion would occur in the channel under today's conditions that would not have occurred under pre-developed conditions. As compared to the hydrograph matching or duration control methods discussed above, the $Q_{critical}$ approach leads to less over-design of solutions, as less storage is needed to achieve the critical flow than matching hydrographs, lowering construction costs and maintenance time.

To achieve this goal of managing storm water towards the $Q_{critical}$ value of a given stream, post-construction storm water controls in several communities now require long-term (e.g., 50 years) modeling of continuous rainfall simulations to demonstrate that:

- 1) The cumulative durations of all flow magnitudes that have the potential to erode the receiving stream do not depart from the cumulative durations of the pre-developed scenario by more than 10% (e.g., San Diego, 2011), or
- 2) The ratio of the cumulative erosion potential, also referred to as 'effective work' or cumulative sediment transport capacity, of the post-developed regime to that of the pre-developed regime does not exceed 1.0 (Santa Clara, 2004).

4.2a Sediment Transport Modeling (Continuous Simulation)

Because excess runoff volumes of larger storms can greatly exceed those of smaller storms, analyses show that the erosion potential approach (i.e., matching the *long-term sediment transport*) is more cost-effective than duration controls (i.e., matching the *long-term cumulative flow durations*) or hydrograph matching (e.g., Goodman, 2013). For example, matching the long-term sediment transport allows for over control of the small and intermediate flows to compensate for excess durations of larger storms, such as the 10- or 50-year event. Such tradeoffs may result in the same amount of total erosion potential in the stream, but require somewhat smaller storage volumes for excess storm water runoff.

SD1 has implemented the sediment transport matching approach on several pilot projects such as the Pleasant Run Inflow and Infiltration (I/I) Project and a detention basin retrofit project being sponsored in

part by the USEPA/ORD. The approach has been vetted by the scientific peer-review process (see Hawley *et al.*, 2012b) and commended by the editor of the *Watershed Science Bulletin* as “an excellent case study... [of] a highly relevant topic facing jurisdictions.” On new development sites, the approach ensures that storm water controls are optimized to match the cumulative sediment transport capacity of the pre-developed regime over long-term simulations (e.g., 50 years) of actual rainfall. In watersheds with existing development and channel instability, retrofitting and/or installing new controls should be evaluated to determine the most cost-effective and feasible alternatives to reduce the post-development sediment transport capacity toward that of the pre-developed condition. However, it is not recommended to attempt to match pre-developed conditions in these settings without regard for cost.

For example in the Pleasant Run pilot project, an analysis found that using cost effective storm water controls (i.e., surface storage ranging from ~\$140,000-230,000), the excess sediment transport capacity of the urban flow regime could be reduced by approximately 55 to 90%. Alternatively, to nearly achieve the original goal of 100% reduction of sediment transport, it would have required additional underground storage chambers, costing approximately \$2 million (Hawley *et al.*, 2012b). The reasonable decision was to achieve the 90% reduction for \$230,000, and save the \$1,770,000 in rate payer resources for investments in cost-effective controls in other neighborhoods. A graphical representation is provided in Figure 21.

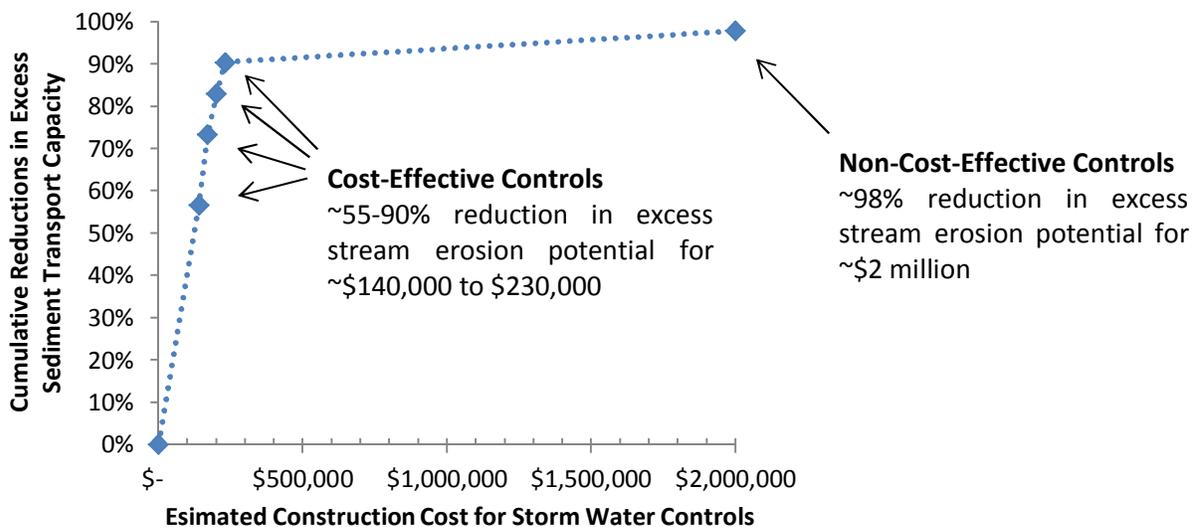


Figure 21. Cumulative reductions in excess stream erosion potential relative to pre-developed conditions vs. estimated construction costs for storm water controls (Adapted from Hawley *et al.*, 2012b).

4.2b $Q_{critical}$ Design

For the Northern Kentucky setting, regionally-calibrated modeling by Sustainable Streams, Strand, and others has determined that there are several simplification steps that can be taken to achieve the same goal of long-term sediment transport matching. First, pseudo-continuous modeling may take the place of continuous modeling because the large majority of rainfall events over a 50-year record will not exceed $Q_{critical}$ and, consequently, not cause channel erosion. To match the long-term sediment transport capacity of the pre-developed regime, it is only necessary to model events that exceed $Q_{critical}$.

which will require a relatively small subset of events from a 50-year record (e.g., the top 20 to 100 events over a 40- to 50-year rainfall record depending on the $Q_{critical}$ threshold of the receiving stream).

Modeling has also demonstrated that a second simplification step may be taken on development sites less than 100 acres. The regional $Q_{critical}$ memo (Sustainable Streams, 2012b) has shown that by optimizing storm water controls to meet a simple design criterion, in addition to meeting the water quality and flood control criteria, designers can achieve the same goal of matching the long-term sediment transport capacity that would be achieved using continuous simulation and sediment transport modeling. For development sites less than 100 acres, the simple design criterion is to control all storms up to and including the 2-year 24-hour event such that they are released at a flow magnitude that is less than $Q_{critical}$ of the receiving stream. SD1 has a database of $Q_{critical}$ values for regional watersheds; however, if a specific $Q_{critical}$ value is unavailable, the regional value of ~40 to 50% of the pre-developed Q_2 (as discussed in Section 4.1) may be used as a surrogate. This regional value scales to a maximum discharge rate of 0.36 to 0.45 cfs per acre of development, for sites draining less than 100 acres for all rain events less than or equal to the 2-year design storm (Sustainable Streams, 2012b). These simplification steps are summarized in Table 3 below.

Table 3. Storm water management for stream stability in Northern Kentucky: sediment transport (continuous simulation) vs. $Q_{critical}$ design.

Storm Water Design Criteria	Developments < 100 acres ¹	Developments > 100 acres ¹ or Watershed-scale Master Planning
Water Quality Volume	0.8 inches	0.8 inches
Channel Protection (Hydromodification)	All storms up to and including the 2-year storm to be released below $Q_{critical}$	Continuous or pseudo-continuous long-term simulations ² of sediment transport capacity ³ of the post-developed regime not to exceed the pre-developed regime ⁴
Flood Control	Post-developed peak flows not to exceed pre-developed peak flows for 2-, 10-, 25-, 50-, and 100-year design storms	Post-developed peak flows not to exceed pre-developed peak flows for 2-, 10-, 25-, 50-, and 100-year design storms

¹Sites draining to streams with more restrictive needs, such as outstanding resource waters, impaired waters, or streams with more specific biogeochemical data may require alternative controls.

²'Long-term' defined as a representative period of continuous rainfall of 40 to 50 years from a Northern Kentucky gage. 'Pseudo-continuous' defined as selectively modeling all storms from a period of continuous rainfall that exceed or have the potential to exceed the $Q_{critical}$ for the downstream channel.

³Sediment transport capacity to be modeled for the bed-material particle range that controls the overall stability of the channel using a method/equation that has been validated in the Northern Kentucky setting. Alternative methods such as 'effective work' or 'erosion potential' may be employed in the place of sediment transport capacity, provided that the modeler demonstrates applicability of the method to the stream setting.

⁴On new development, controls should match the pre-developed regime; however, on redevelopment projects or in watersheds with existing development that lack abundant opportunities for cost-effective controls, designs should be evaluated that cost-effectively improve the existing conditions to the maximum extent practicable but should not be taken to the extent of fully matching the pre-developed regime without regard for non-linear increases in costs.

In practice, achieving the $Q_{critical}$ design goal, in addition to the water quality and flood control objectives, should not result in substantially higher costs than traditional storm water control. As shown in Table 4, Sustainable Streams and Strand were able to optimize the outlet control structure of a bioretention basin in a pilot study to achieve the sediment transport goal of no net increase over the pre-developed condition using a smaller footprint than that of the conventional detention basin, which, without optimization created a stream erosion regime that is ~1,000% worse than the pre-developed scenario (Sustainable Streams, 2012b). Continued stream stability monitoring by SD1 and regional partners to document the efficacy of such simplified approaches will confirm whether these approaches achieve the desired results in the streams, and/or if they need to revisit and revise the approach(es).

Table 4. Comparison of flow durations and sediment transport amounts for various detention types, based on policy standards (SD1 2012; 2013).

Detention Type	Policy Standards	Basin Footprint	Hours of Flows Larger Than $Q_{critical}$	Tons of Sediment Transport
		SF	% Difference	% Difference
Pre-Development	N/A	--	--	--
Post-Development	No Control	--	903%	1145%
Detention	Peak matching	9,500	516%	290%
Bioretention	WQ & Peak	8,935	120%	197%
Bioretention	WQ ,Peak and $Q_{critical}$	8,935	32%	-11%

4.3 Storm Water Controls for Improving Channel Stability

There are many types of storm water controls that can be utilized to improve the stability of channels. Retrofitting existing detention basins is a cost-effective approach that utilizes existing controls that have less than desired performance (in terms of protecting streams from erosion). As previously discussed, conventional detention basins are designed for flood control and match peak flow rates for storms as small as the 2-year event. For all storms less than that, which includes essentially all storms in a typical year, existing control designs have little to no attenuating effect (Emerson *et al.*, 2003; Hawley, 2012). By retrofitting these basins, smaller events can be detained to reduce the excess erosive power on the receiving stream, without adversely impacting the flood control performance of the basin.

Though retrofits present a highly feasible opportunity, new storm water controls may be needed within a watershed as well. Bankfull wetlands, bioretention basins, and detention basins are all viable options to manage storm water for $Q_{critical}$ and promote downstream channel stability. These storm water controls increase the storage volume to detain erosive flows prior to discharging to a stream. Other benefits include sediment deposition, nutrient uptake, and relatively inexpensive construction costs. Figure 22 (included in the Gunpowder Creek Watershed Plan (GCWI, In review)) provides an example cut sheet for some controls mentioned above.

Conventional detention basins, which are designed for flood control, have little attenuating effect on essentially all storms in a typical year and can create 300-500% more erosion potential in receiving streams than pre-developed conditions.

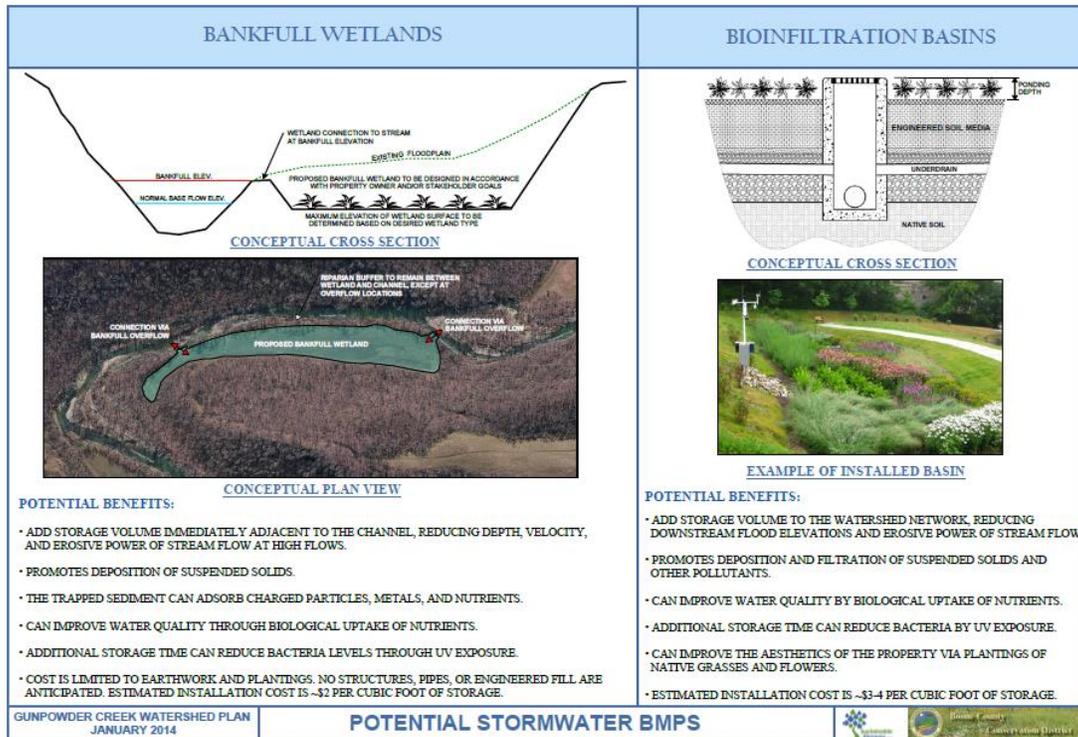


Figure 22. Example cut sheet for storm water controls designed to address $Q_{critical}$ (GCWI, In review).

Stream restoration, including reconstruction and stabilization, can be another useful tool to improve channel stability, but must be evaluated on a project-specific basis. To properly restore a stream reach, it is imperative that the underlying causes of the problem are accurately identified and addressed in order to adequately design a sustainable, long-term solution. In urban/suburban areas (where this has not typically been the case), successful and cost-effective stream stabilization has been challenging to achieve. For example, SD1 recently completed two stabilization projects along Dry Creek and Pleasant Run, totaling approximately 1,200 feet in length and ~\$1.45 million in construction costs combined. Since 2008 when the projects were constructed, flanking, headcut migration, and cross vane undercutting are prevalent in the project locations (Hawley *et al.*, 2013a).

Beyond limited success in achieving channel stability, reach-scale stream restoration efforts have shown little success in improving biological community health, especially in urban settings (Palmer *et al.*, 2010), and the urban flow regime has often been cited as a primary reason for the lack of such success (Violin *et al.*, 2011). For this and other reasons, Portland, Oregon no longer invests in reach-scale stream restoration efforts unless the watershed-scale impairments have been adequately addressed (Portland, 2005, Table 2-1). Although reach-scale efforts may still be necessary to protect imperiled infrastructure, it is increasingly recognized that watershed-scale storm water efforts may be more sustainable.

Watershed-scale storm water controls may also be less expensive when compared to conventional stream restoration construction (Figure 23; Hawley *et al.*, 2013a). This could particularly be the case when space is available for surface storage controls, which tend to be an order of magnitude less expensive than subsurface storage. The case is even stronger for the storm water-based approach in watersheds where detention basin retrofits are a feasible alternative, as they tend to be 10- to 100-times less expensive than constructing new controls (Hawley *et al.*, 2013a). This cost-effective approach is discussed further below (Section 5.0).

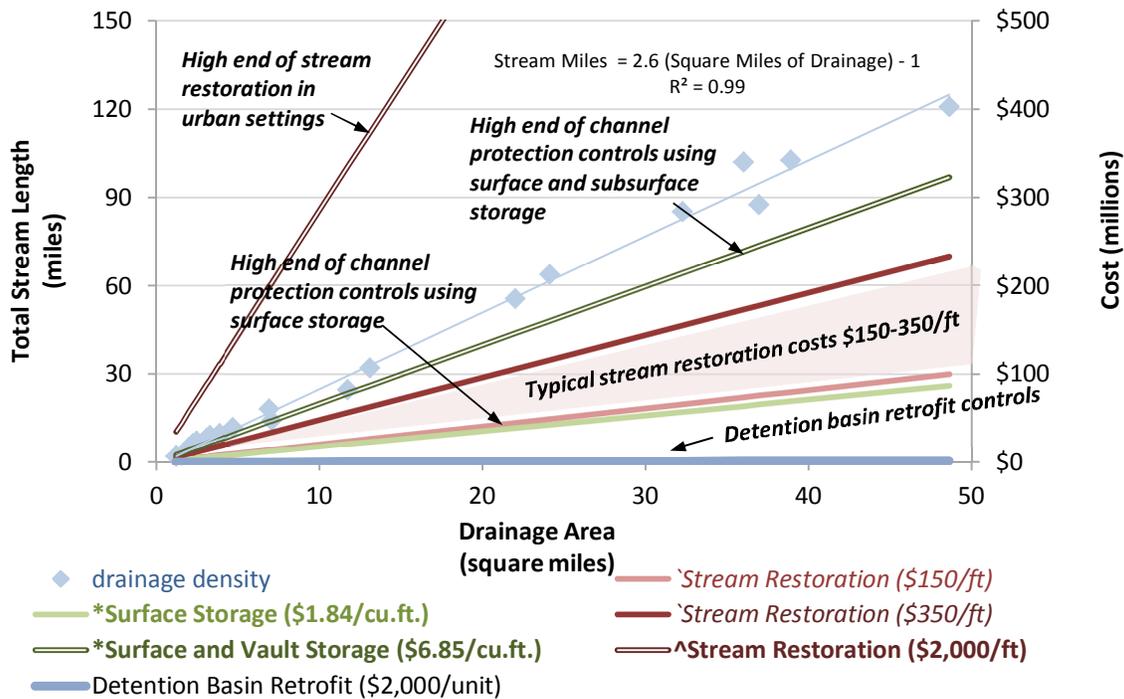


Figure 23. Cost comparison for stream restoration and channel protection costs (Hawley et al., 2013a).

- (a) Drainage densities via collaboration with Dr. Brian Lee and Corey Wilson (Univ. of Kentucky)
- (b) Stream restoration costs of \$150 - \$350 per foot are typical ranges for small (mostly) rural stream settings.
- (c) Storage requirements for channel protection of ~1 million cubic feet of storage per square mile of drainage area are based on storage requirements for a project in a watershed with 26% impervious area with no existing detention, a $Q_{critical}$ design of 30% of the 2-year peak flow magnitude, and design alternatives that included surface and subsurface storage after Hawley et al. (2012b).
- (d) Stream restoration cost of \$2,000 per foot is based on an actual N.KY. project in a watershed with 26% impervious area and little upstream storage.

5.0 Pilot Projects Assist in Evaluating Potential Storm Water Management Approaches

5.1 SD1 Pilot Projects Support this Approach

In order to facilitate the development of appropriate controls, SD1 has collected hydrogeomorphic data to calibrate controls using modeling. Additionally, the monitoring program has been employed to evaluate the efficacy of the proposed management concepts. SD1 has been involved with efforts on local pilot projects for the control of storm water with an emphasis on $Q_{critical}$ and hydromodification in an effort to advance the regional understanding of channel protection strategies, as well as evaluate their costs and effectiveness.



Figure 24. Collecting hydrogeomorphic data on Pleasant Run Creek at PRC2.8

5.1a Vernon Lane and Pleasant Run

The Vernon Lane and Pleasant Run projects mentioned earlier (Sections 4.1) are examples of hydromodification pilot projects that incorporate channel protection goals into otherwise routine I/I projects. Cross section, profile, and bed material data were collected at four locations within each project's drainage area (Figure 24), along with biological and habitat data. The hydrogeomorphic data were then used to develop estimates of $Q_{critical}$, as well as optimize and evaluate storm water control alternatives to minimize the cumulative sediment transport capacity of the flow regime in order to improve downstream channel stability (Hawley *et al.*, 2012). As previously discussed (Section 4.2), substantial benefits could be achieved using cost-effective surface storage; however, sub-surface storage was required to nearly achieve the goal of 100% reduction of the excess sediment transport capacity relative to the pre-developed regime (Figure 21). Because the cost between the surface controls and the additional subsurface controls was an order of magnitude different (~\$200,000 vs. ~\$2 million), it was decided to invest in the more economical approach for the pilot effort. Once construction is complete, continued monitoring to document the benefits from these projects in the adjacent streams is crucial to project success. Monitoring may discover that the \$200,000 solution was sufficient to restore relative stability in the receiving streams, which could further save resources on future projects. SD1 is currently moving forward with the Vernon Lane Project, as it is progressing into the preliminary design phase.

5.1b Horse Branch

Horse Branch, as mentioned earlier (Section 4.1), is a highly unstable stream that is dangerously close to causing roadway instability (Figure 25). This roadway depicted in Figure 25 is heavily utilized by the St. Elizabeth Hospital, a potential project partner that has nearly no storm water detention onsite. Edgewood and Crestview Hills, the two cities located within the watershed, are additional partners for implementation. SD1 has already been a partner in promoting a holistic, watershed-based approach by funding a modeling effort to assess the potential effectiveness of detention basin retrofits in the watershed. Modeling shows that without installing any new storm water controls, retrofitting approximately 16 existing detention basins, estimated to cost \$80,000, could reduce the excess sediment transport capacity by 20 to 25%. Although this would be unlikely to completely stabilize Horse Branch, it could go far in reducing the rates of instability in the channel, as well as make the need for new controls potentially more manageable.



Figure 25. Horse Branch is dangerously close to causing roadway instability.

5.2 Regional Efforts Also Support SD1's Approach to Providing Channel Protection

In addition to the above-mentioned pilot projects, there are numerous regional efforts in which SD1 has partnered to improve stream system integrity.

5.2a Toyota Basin Retrofit with USEPA

The Toyota Basin project, which is a detention basin retrofit project located on a Toyota warehouse distribution site in Hebron, Kentucky, is currently the pilot site for a simple device that is designed to control basin outflows to reduce the cumulative erosion in the receiving stream. The retrofit device is

designed to function by reducing the duration of flows that exceed $Q_{critical}$ to ultimately decrease the cumulative sediment transport potential of the flows that are discharged from the basin. Project partners include USEPA/ORD, SD1, BCCD, Sustainable Streams, Strand Associates, CBI, and ISCO. This product has been well received by both the USEPA and KDOW for its innovative approach and for its merits in improving water quality (presented to the Mississippi River Gulf of Mexico Watershed Nutrient Task Force at the Hypoxia Task Force Meeting in 2013 (Hawley *et al.*, 2013c), as well as WEFTEC (Goodrich *et al.*, 2014)) and complying with the Clean Water Act.

The device, seen in Figure 26, was designed to restrict the release of most storms in order to reduce stream erosion and enhance water quality treatment. To monitor the impacts, data are currently being collected both at the site and surrounding locations. Flow monitoring at the site began in 2013, prior to installation of the retrofit device. Inflow and outflow hydrographs have been analyzed, along with rainfall data collected from a gage at the site and at the Cincinnati/Northern Kentucky International Airport (CVG). Pre-installation, the hydrographs show very flashy outflows, with little delay in the peak from the time of inflow to outflow. While post-installation data are still being collected, preliminary analyses indicate that the peaks in the outflow hydrograph are more delayed following the inflow peak, when compared to pre-installation data. Two specific storm events underscore the potential benefits of the device: a pre-retrofit event from October 31, 2013 and a post-retrofit event from April 3, 2014. Although there is no inflow data from the pre-retrofit event, the outflow peaked at more than 6 cfs for less than 1 inch of rain. In contrast, the post-retrofit event peaked at an outflow less than 6 cfs with considerably more rain (2 inches) and a peak inflow rate of greater than 10 cfs (Table 5). In addition to benefits regarding channel erosion, water quality performance is also anticipated to be improved via a doubling of basin residence time in the typical year.



Figure 26. Detention basin retrofit device for reducing hydromodification impacts to adjacent streams.

Table 5. Summary of comparable pre- and post-installation events.

	Total Precipitation (in)	Peak Intensity (in/hr)	Peak Inflow (cfs)	Peak Outflow (cfs)
Pre-retrofit: October 31, 2013	0.9	0.3	Unknown	6
Post-retrofit: April 3, 2014	2.0	0.4	11.1	5.3

5.2b Gunpowder Creek

In 2009, BCCD was awarded an \$835,000 319(h) grant to develop a watershed plan for this 58-square mile watershed. Segments of Gunpowder Creek are listed as impaired on KDOW's 303(d) list primarily for high levels of bacteria, sediment, and nutrients. Through sewer system improvements, SD1 is currently mitigating Sanitary Sewer Overflows (SSOs), which are one of the likely historical sources of impairment. Sediment and turbidity are also two of the listed pollutants by KDOW, and as discussed above (Section 3.3), monitoring has confirmed that sediment is the dominant pollutant and streambank erosion, induced by inadequately controlled storm water runoff, is the primary source of sediment. It is in SD1's and the community's interest to see Gunpowder Creek removed from the 303(d) list to preclude the development of a total maximum daily load (TMDL) for sediment, as a TMDL for bacteria is

already under development. TMDLs can have large associated cost burdens to regulated utilities, and therefore, it is logical that ongoing capital investments by SD1 in the watershed should do everything feasible to begin to lessen these storm water-induced sediment loads, or at a minimum, not make them worse.

BCCD has taken great care to be consciously cost-effective, where able, in order to save some funding to construct and cost-share projects that are consistent with the goals of the watershed plan. For example, BCCD was able to utilize existing SD1 stream monitoring data and use SD1 staff and students for additional monitoring. These cost savings have allowed BCCD to cost-share with other project partners, for example, possibly with the City of Florence to make greater water quality and channel erosion improvements to projects Florence was already planning.

5.2c Woolper Creek

The Woolper Creek Watershed has a similar story to that of Gunpowder Creek. The Woolper Creek Watershed is 33 square miles and is also suffering from urbanization, although the urbanization in this watershed is more recent and less extensive compared to Gunpowder. In 2010, BCCD was awarded a \$750,000 319(h) grant to develop a watershed plan for Woolper Creek. Again, BCCD has been diligent in saving money through their monitoring efforts and other expenditures in order to have remaining funding for project implementation after writing the Watershed Plan.

The implementation funding could support efforts in areas such as Allen Fork/Darlington Farms, which has documented flooding and sedimentation issues by local residents. The Allen Fork Subwatershed, which is the most developed area in the Woolper Creek Watershed, is undergoing the initial phases of instability from development and has been experiencing flooding and channel erosion. An important partnership in this area of the watershed includes NKU CER, which has already invested ~\$470,000 in restoring 4,400 feet of stream and 0.2 acres of storm water wetlands in the headwaters of Allen Fork. Water quality data suggest that if stream stability improves in Allen Fork through the installation of storm water controls and/or detention basin retrofits, Allen Fork may be able to be removed from the 303(d) list (WCWI, In prep), which would preclude the need for KDOW to develop a TMDL that might otherwise put onerous requirements on SD1. A delisting of Allen Fork, or any stream within NKY, would not only be beneficial to SD1, but it would also be beneficial for all parties involved including BCCD, USEPA, and KDOW.

5.2d Banklick Creek Detention Basin Retrofits

The Banklick Watershed Council, in partnership with SD1 has also pursued the pilot installation of detention basin retrofits. One of the basins involved a simple installation of a plate to restrict the outflow from the low flow orifice, as well as the installation of a new window in the outlet control structure. The other basin retrofit involved a more invasive approach, using construction equipment to install engineered soils in the bottom of the basin and facilitate the conversion to a bioretention basin for improved water quality performance and aesthetics. Both projects have been modeled to show positive effects for downstream channel stability, indicating that detention basin retrofits may not need to be a one-size-fits-all approach.

5.2e Public Education and Outreach Illustrates Concerns Related to Flooding and Erosion

Furthermore, these regional partners and watershed groups are increasingly understanding and documenting the connection between conventional storm water management and problems downstream, such as erosion, flooding, and water quality. They are also active in the public education

process and have raised issues to the SD1 Board, as well as other regional stakeholders, such as the fiscal courts. They can be strong advocates for taking hydromodification into account during design

It is important to note that the public has become increasingly vocal about their concerns related to flooding and erosion, as well as their impression that inadequate storm water runoff controls and poor development practices are the primary cause of the problems (Table 6). Therefore, it can be said that a growing number of SD1's customers are advocating better control of hydromodification, including its downstream effects on both flooding and stream instability.

Table 6. Summary of questions and dominant responses from approximately 70 participants at a Gunpowder Creek Watershed public meeting illustrates that runoff and flooding are the most concerning problems in the watershed.

Question	Dominant Responses ⁽¹⁾
1. Why is a clean healthy stream important to you?	Recreation (73%), Aesthetics (66%), Quality of Life/Health (54%)
2. What land uses in the watershed are you most concerned about?	Development (100%)
3. What do you think are the most common problems?	Runoff (73%), Flooding/Safety (66%)
4. What BPMs do you consider feasible in Gunpowder Creek?	Detention/Retention (82%), Education (66%), Responsible Development/Ordinances (55%)
5. What issues in Gunpowder Creek do you consider a priority?	Storm Water Runoff (66%), Flooding (55%)

⁽¹⁾Responses that were listed by more than half of the groups.

Ultimately, these examples highlight the need for master plans that identify cost-effective opportunities to improve flooding, water quality, and channel stability throughout the stream network via strategic implementation of new storage and/or optimization of existing storage in order to achieve greater cumulative benefits at less cost. Otherwise, it may begin to seem disconcerting to ratepayers that multimillion dollar investments are made to move a flooding problem from one neighborhood to others downstream when ten thousand dollar efforts like detention basin retrofits can begin to address the problems at the source.

6.0 SD1's Approach has been Scientifically Vetted and is Supported by Regulators

6.1 Publications

Nationally, SD1's hydromodification program has been commended as an innovative, science-based approach. The approach has been vetted by the scientific community through peer reviewed papers that have been published in scientific journals in the last two years, and SD1 staff and consultants have been invited to present the program at numerous regional, national, and international conferences. The

listings below are only a sample set of the publications that have resulted from SD1's hydromodification program.

Two papers have been published in peer-reviewed journals including the Pleasant Run/Vernon Lane pilot study discussed above (Section 5.1a) published in the *Watershed Science Bulletin* by the Center for Watershed Protection, and the bed coarsening/riffle shortening paper (Section 3.1) published in the internationally-respected journal *Geomorphology* by Elsevier (Figure 27). The case study of Middle Creek, discussed in Section 3.3, was presented at the Fall Meeting of the American Geophysical Union, an annual gathering of approximately 20,000 earth scientists. The Toyota Basin project, discussed above (Section 5.2a), was recently presented to the National Water Quality Monitoring Council (NWQMC) and WEFTEC, an annual gathering of approximately 20,000 water industry professionals. Moreover, SD1 was invited to present at a special WEFTEC session on the hydromodification program as a whole.

6.2 Regulators Show Support for SD1's Approach

In addition to the regional partners discussed above, USEPA, KDOW, and US Senators have commended SD1's approach for channel stability. For example, in April of 2014, the US Senate held a hearing to highlight the impacts of highway runoff on stream pollution and the need to address it. SD1 was invited to provide testimony on some of the impacts discussed above and emphasized the importance of using regionally-calibrated approaches to cost-effectively manage storm water in ways that are most appropriate and beneficial for the region (Gibson, 2014). The SD1 hydromodification program can go far in developing an evidence-based case for KDOW, USEPA, and other regulators to allow SD1 the necessary flexibility to achieve the goals of the Clean Water Act in ways that are most appropriate for Northern Kentucky.

Next, national and state regulators are increasingly promoting and requiring storm water management approaches that are intended to protect streams against excess erosion and hydromodification. These include states surrounding Kentucky, such as Tennessee, Ohio, and West Virginia. It remains to be determined how effective some of these approaches will be at protecting stream stability; however, EPA's own analyses have documented that some of these generic approaches (e.g. onsite retention of 1") may have excess costs and/or be infeasible in soils with poor infiltration (Pritts, 2014). As an alternative to the generic approaches, both the USEPA (Gibson, 2014) and KDOW are aware of the regionally-calibrated $Q_{critical}$ methodology and support its use in Northern Kentucky. Within the last two years, SD1 staff have been invited twice to Washington, D.C. and once to Frankfort, KY to discuss aspects of the program with USEPA, the United States Senate, (Figure 28), and KDOW, respectively. Continued education to national and state regulators will assist in making the cost-effective Northern Kentucky approach acceptable to regulators.



Figure 27. SD1's Hydromodification Monitoring Program results were published in Geomorphology, an internationally-respected journal (Hawley et al., 2013a).



Figure 28. SD1's hydromodification program has been nationally recognized as evident by its invitation to speak at a Hearing of the U.S. Senate.

7.0 Outreach to Local Stakeholders

SD1 continues to create opportunities to inform local stakeholders of this cost-effective approach to channel stability. First, SD1 provides annual training opportunities to local engineers and developers on the storm water program. In December 2014, training provided specific, step-by-step guidance on how to incorporate cost-effective solutions for channel protection into flood control and water quality controls that are already required. At this and other venues such as the KYTC Annual Partnering Conference (Wooten and Hawley, 2014), SD1's training presentations included examples specifically targeted to transportation projects using amended swales—a BMP that is simply an adaption of typical highway ditches and would not require additional right-of-way as compared to detention facilities. Regional engineers and developers are encouraged to capitalize on these and future training opportunities such that they can obtain the step-by-step know-how to design for $Q_{critical}$ without substantially increasing project costs in most cases.

Training and education for local leaders will be important in order to provide an understanding of what types of approaches are necessary to adequately protect streams from excess erosion and flooding downstream when addressing local storm water issues. These efforts not only protect stream quality, but protect our region's infrastructure and built environment such as roads, bridges, and sanitary sewer lines.

8.0 Conclusion

Although several regions across the United States have started to implement channel protection controls to protect/restore stream integrity (e.g., Figure 29), the concept of designing storm water controls to address hydromodification concerns is not prevalent throughout most of the United States. In reviewing other design methodologies, SD1 has learned that these other approaches may not be appropriate for the Northern Kentucky region, and therefore, SD1 has taken a data-driven approach to understanding the condition of local stream systems and developing a regionally-calibrated approach to channel protection throughout Northern Kentucky. Beginning in 2008, SD1's Hydromodification Monitoring Program has grown to include a robust database of approximately 60 stream monitoring sites with data across three channel dimensions (i.e., cross section, profile, and bed material). This data has provided a strong foundation for the development of a stream condition assessment tool, along with an approach for channel protection - designing storm water controls to consider $Q_{critical}$. This approach is relatively simple on small development projects (i.e., less than 100 acres), as design engineers only need to adjust for the 2-year peak flow. Sediment transport modeling is recommended on storm water master planning developments with drainage areas to an individual storm water facility (e.g. a detention basin) that exceed 100 acres. When compared to methodologies such as full-scale duration controls or hydrograph matching, this approach is expected to be more cost-effective for the Northern Kentucky region.



Figure 29. Double Lick Creek serves as an example of regional stream integrity and exhibits quality habitat and biotic communities and is one of SD1's reference sites.

SD1 has been leading and teaming on pilot projects across the Northern Kentucky region to continue to study and understand the effectiveness of a regional approach to hydromodification. To date, results in various watersheds have shown a positive impact on the flows with extremely cost-effective solutions, and there are ample opportunities for future projects and partnerships. Both state and federal regulators have supported SD1's methodology as well, and continue to think of SD1 as a leader on hydromodification. Furthermore, SD1's hydromodification approach also has the potential to reduce SD1's regulatory burden. For example, Allen Fork, which is located in the Woolper Creek Watershed, is a 303(d) listed stream, but monitoring data show that it is primarily caused by hydromodification. Retroactively improving storm water facilities to reduce hydromodification in the Allen Fork watershed could contribute to measurable improvement in the hydrology, stability, and biology of Allen Fork, and help to facilitate a removal of the stream from the 303(d) list. Doing so in advance of a TMDL development, which can otherwise mandate investments and discharge limits, could eliminate mandatory investments by KDOW that may not be as cost-effective as a regionally-developed approach.

It is clear through the diligent efforts conducted to date that restoring stream integrity, minimizing hydromodification, protecting at-risk infrastructure, and doing so in an efficient and cost-effective manner, are all core values of SD1. SD1 plans to continue to expand these efforts through continued educational opportunities for local developers, engineers, and other interested stakeholders and advancing projects with a focus on hydromodification. Continued implementation and monitoring efforts will document success in the streams, and SD1 could potentially improve a stream on the 303(d) list as a result of storm water controls focused on mitigating hydromodification. These efforts would provide ultimate validation of the program and provide the endpoint that regulators need in order to fully embrace the SD1 approach.

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