ABSTRACT

Title of Thesis: REGENERATIVE STORMWATER CONVEYANCE: DESIGN IMPLICATIONS OF AN URBAN CASE DEMONSTRATION IN BALTIMORE, MARYLAND

Kathleen Hayes
Master of Landscape Architecture, 2016

Directed by: Dr. Victoria Chanse
Department of Plant Sciences
and Landscape Architecture

This research-design thesis explores the implementation of Regenerative Stormwater Conveyance (RSC) as a retrofit of an existing impervious drainage system in a small catchment in the degraded Jones Falls watershed in Baltimore City. An introduction to RSC is provided, placing its development within a theoretical context of novel ecosystems, biomimicry and Nassauer and Opdam's (2008) model of landscape innovation. The case site is in Baltimore's Hampden neighborhood on City-owned land adjacent to rowhomes, open space and an access point to a popular wooded trail along a local stream. The design proposal employs RSC to retrofit an ill-performing stormwater system, simultaneously providing a range of ecological, social and economic services; water quantity, water quality and economic performance of the proposed RSC are quantified. While the proposed design is site-specific the model is adaptable for retrofitting other small-scale impervious drainage systems, providing a strategic tool in addressing Baltimore City's stormwater challenges.

REGENERATIVE STORMWATER CONVEYANCE: DESIGN IMPLICATIONS OF AN URBAN CASE DEMONSTRATION IN BALTIMORE, MARYLAND

by

Kathleen Anne Hayes

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Landscape Architecture
2016

Advisory Committee:
Dr. Victoria Chanse, Chair
Dr. Christopher Ellis
Dr. Peter May

Acknowledgements

It is a pleasure to express my deep thanks and gratitude to my committee members and mentors Dr. Victoria Chanse, Dr. Christopher Ellis and Dr. Peter May. Their knowledge, timely advice and unwavering enthusiasm were critical in allowing me to achieve the goals I set for myself when embarking upon this thesis process.

The choice to do a thesis project on a relatively new technique for which the literature has only recently begun to be established created numerous challenges. Without the generosity of practitioners who are implementing and developing Regenerative Stormwater Conveyance in the field, this thesis would never have been possible. My sincere gratitude goes out to Keith Underwood and Joe Arrowsmith of Underwood & Associates, Nick Lindow of CityScape Engineering and Chris Streb of Biohabitats for sharing their time and expertise with me.

Contents

List of Tables

List of Figures

Introduction

This research-design thesis explores the application of Regenerative Stormwater Conveyance (RSC) to retrofit an existing impervious drainage system in a small 2.75 acre (1.12 ha) catchment in the degraded Jones Falls watershed in the City of Baltimore. A relatively new stream restoration and stormwater mitigation technique, RSC was developed in the early 2000s for use on the coastal plain of Anne Arundel County, Maryland as multifunctional approach to providing stormwater conveyance and treatment benefits, as well as creating habitat, particularly for the globally rare Atlantic White Cedar (*Chamaecyparis thyoides*). Alternatively known as Step Pool Stormwater Conveyance, Biofiltration Conveyance and Coastal Plain Outfall, implementation of RSC has expanded over the past fifteen years to the piedmont physiographic region of Maryland, as well as sites in the broader Mid-Atlantic and North Carolina. Today, RSC is a credited stormwater BMP by the Maryland Department of the Environment (MD DOE 2014) and the EPA Chesapeake Bay Program (WQGIT 2014) and its application is rapidly growing. The flexible design pattern and small installation footprint of RSC make it highly suitable for implementation in urbanized areas, but it has not yet been employed in the City of Baltimore; nor has it typically been employed on the small site scale of the case demonstration.

This thesis provides an introduction to the components, characteristics and benefits of RSC, followed by a discussion the development of RSC within a theoretical context of novel ecosystems, biomimicry and Nassauer and Opdam's (2008) iterative model of landscape innovation. The case demonstration presented here investigates the potential of implementing RSC in the City of Baltimore as an innovative Green Infrastructure strategy in addressing the City's stormwater challenges.

CHAPTER 1 Regenerative Stormwater Conveyance

Regenerative Stormwater Conveyance (RSC) is an open channel headwater stream restoration and stormwater control measure consisting of a porous sand media bed, shallow riffle/weir step pools and native vegetation. By combining features of swales, bioretention and wetland practices, RSC converts surface stormwater runoff to shallow groundwater flow and non-erosive surface flow for up to the 100-year storm (Filoso and Palmer 2011; Brown, Berg, and Underwood 2010; Brown et al. 2015), while simultaneously capturing, detaining, treating and infiltrating stormwater runoff. Each of the components of RSC component offers hydrologic and water quality benefits.

Figure 1. Photos of RSC (Biohabitats)

Components of RSC Systems

Riffles and Pools

Reflective of stream geomorphology, the riffles and pools of RSC serve to reduce water velocity and allow for infiltration into the porous media bed. In dissipating the energy of stormwater runoff, the vegetated pools allow for sedimentation of suspended particles and their associated pollutants and nutrients (Brown, Berg, and Underwood 2010). This provides a rich media for vegetation growth, generating further water quality treatment, as well as habitat and aesthetic benefits (Cizek 2014). The riffle weirs set the surface water elevations in the pools and provide the hydraulic head required to establish the sand seepage hydrology that drives the RSC system (Brown, Berg, and Underwood 2010). The riffle–pool sequence limits both the velocity and the depth of runoff during large precipitation events and spreads runoff flow horizontally, thereby mimicking floodplain hydrology (Kaushal et al. 2008) and maintaining non-erosive flow for up to the 100-year storm peak volume (H. Flores et al. 2009; Brown, Berg, and Underwood 2010).

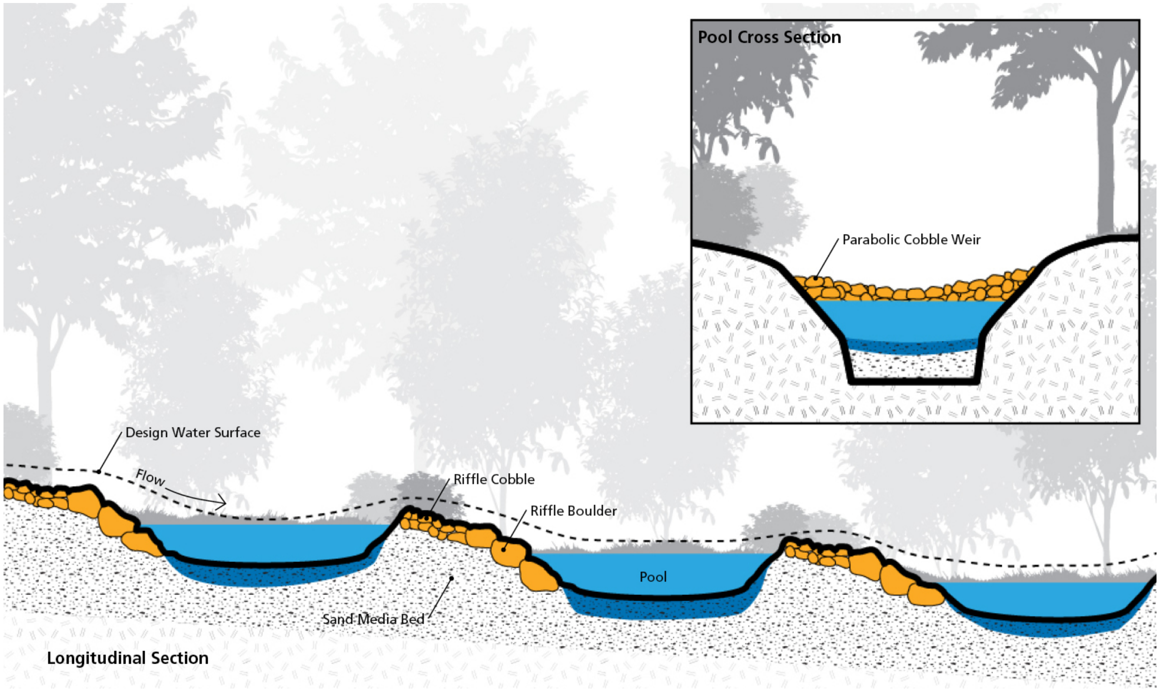


Figure 2. The riffle–pool sequence

Porous Media Bed

The bed material beneath the riffles and pools is a porous, carbon-rich mixture of sand and shredded green hardwood mulch. Locally quarried sand with a 0.02–0.04 inch (0.5–1 mm) particle size is mixed with typically 20 percent freshly shredded hardwood—often sourced from the site itself or local land development projects. The media bed is designed to have high hydraulic conductivity facilitating infiltration of runoff into the media bed (Cizek 2014). The media bed filters sediments and retains stormwater runoff in the voids. Fungal and microbial communities make use of the carbon from the hardwood as well as the excess nutrients in the infiltrated stormwater runoff to support their production. This encourages grazing by soil micro- and macro-invertebrates, which further increases the porosity of the media bed, thereby establishing a self-improving feedback (Berg and Underwood 2012; Brown, Berg, and Underwood 2010).

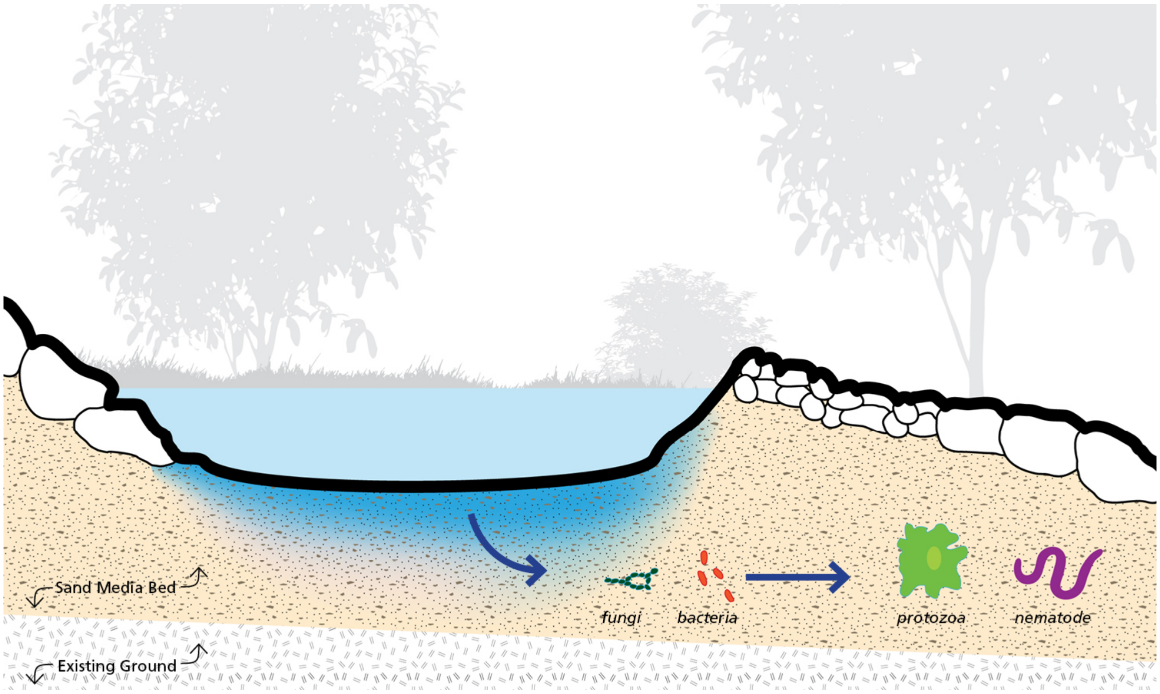


Figure 3. The porous sand–hardwood media bed

Native Plant Community

An established plant community is critical to the regenerative aspect of RSC. Vegetation along the channel and in the bottom of the pools ties the system together providing for flow attenuation, nutrient uptake, evapotranspiration, carbon sequestration. As the roots move through the media bed, they increase porosity, take up nutrients, support microbial metabolism and provide for the adsorption of contaminants (Brown, Berg, and Underwood 2010). The plant community also increases the biodiversity and habitat benefits of RSC while adding to the aesthetics of the RSC system.

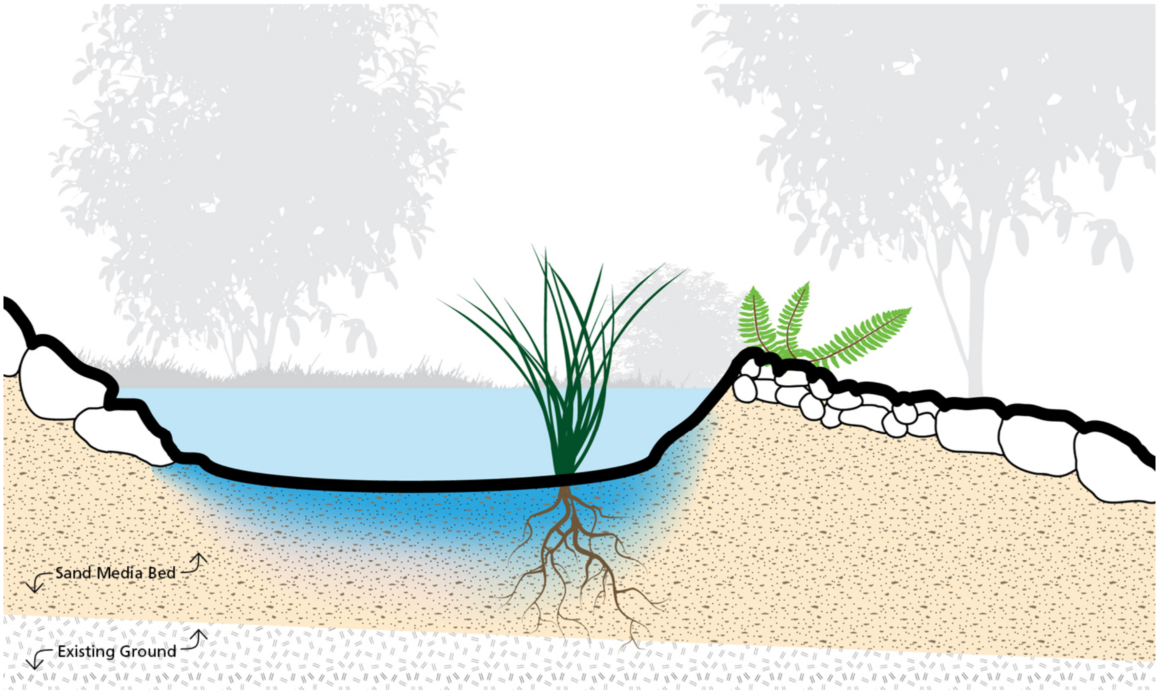


Figure 4. The native plant community

Characteristics and Benefits of RSC

RSC systems are designed to regenerate zero- or first-order headwater stream ecosystems. The unique value of headwater ecosystems comes from their close relationship with the surrounding terrestrial environment, which results in broadly variable habitat conditions supporting of a range of invertebrate communities (Storey et al. 2009). Terrestrial–aquatic ecosystems, such as wetlands and streams, are significant contributors to human wellbeing (Palmer and Richardson 2009), and their ecosystem services have been valued at as much as US$ 6.6 trillion annually (Costanza et al. 1997). RSC systems may be perennially, intermittently or ephemerally wet depending on site conditions and landscape position. They restore an array of site ecologies (Brown, Berg, and Underwood 2010), bolstering a headwater biodiversity that improves the character and function of the downstream ecosystem (Meyer et al. 2007).

RSC systems can further be understood to be regenerative in that they are self-improving systems through the positive feedback mechanism created by the interaction between the microbial and plant communities that improve the surrounding environment, which, in turn, improves the RSC system (Cizek 2014). RSC provides ecosystems services beyond that of stormwater mitigation, creating resource value and functioning as part of the broader ecosystem. Once established, RSC systems have demonstrated the capacity to be self-maintaining and resilient (Brown, Berg, and Underwood 2010).

Finally, RSC landscapes are multifunctional landscapes. As “spatial–human ecological systems,” landscapes deliver a broad array of economic, sociocultural and ecological functions that may or may not be valued by humans, thereby connecting landscape performance to human values and use (Termorshuizen and Opdam 2009). Multifunctional landscapes can be designed to provide an array of ecological, social and economic functions (Sarah Taylor Lovell and Johnston 2008), and the need for multifunctional landscapes is now commonly recognized (O’Farrell and Anderson 2010). Table 1 outlines a number of the benefits of RSC that makes it an ideal candidate for a multifunctional stormwater landscape.

Table 1. Benefits of Regenerative Stormwater Conveyance

Hydrological	• Runoff reduction (safe conveyance of 100-year storm) • Increased Time of Concentration and reduction of Peak Discharges • Groundwater recharge
Water Quality	• Reduction of sediment, excess nutrients, pathogens, and other contaminant loadings in runoff • Thermal regulation
Climate	• GHG reduction through carbon sequestration • Air quality improvement through filtration and/or absorption of particulates and other contaminants by vegetation • Urban heat island mitigation through evapotranspirative heat dissipation
Habitat Provision	• Range of invertebrates, plants, animals, amphibians and insects • Permanent and transient residents
Cultural	• Research and educational opportunities (at all levels) • Aesthetics and recreation • Community involvement and stewardship
Economic	• Small area of disturbance • Low maintenance • "Green-collar" job creation in design and construction

CHAPTER 2 Theoretical Context

Landscapes are continually being altered by humans to increase their perceived value (Termorshuizen and Opdam 2009; Nassauer and Opdam 2008). Such anthropogenic landscapes have been typically been overlooked and undervalued but are more and more coming to be understood as essential to maintaining biodiversity and providing ecosystem services (Bridgewater et al. 2011; Miller and Hobbs 2002; Lundholm and Richardson 2010). Indeed, some argue that achieving sustainability, particularly urban sustainability, will depend on significant landscape innovations (Novotny, Ahern, and Brown 2010), and that the invention of such ecological landscape solutions must come from a perspective that acknowledges humans as components of ecosystems, rather than separate from them (Palmer et al. 2004). RSC is one such ecological landscape solution, designed in response to human-created challenges surrounding stormwater runoff.

Designed ecosystems, such as RSC, are novel ecosystems purposely invented to optimize specific ecological services from interdependent human–natural ecosystems (Palmer et al. 2004). These systems may be designed to alleviate unfavorable conditions by pairing technological innovations with novel assemblages of native species, consciously favoring certain ecosystem functions in order to achieve specific ecological, sociocultural and economic goals (Palmer et al. 2004; Palmer, Filoso, and Fanelli 2014). Novel ecosystems resulting from designed ecological solutions may offer alternative stable states for systems that would be essentially impossible to restore to historical conditions (Beisner, Haydon, and Cuddington 2003; Hobbs et al. 2006), such as the highly urbanized ecosystems where RSC is most commonly implemented. Further, novel ecosystems are valuable from the viewpoint of cultural ecosystems services as they are often the primary places where people connect with nature (Hobbs, Higgs, and Harris 2009; Bridgewater et al. 2011); communities may cherish local natural areas such as streams and woodlands without realizing how far removed they are from their historical conditions.

Nassauer and Opdam's (2008) Model of Landscape Innovation

In their article *Design in Science* (2008), scholars Joan Iverson Nassauer and Paul Opdam posit design—both as process and product—as the essential link between science and practice in forging the type of ecological landscape solutions discussed above. They propose a model comprising three components—analysis, integration and implementation—that function iteratively to generate landscape innovations (Figure 5). The first component, analysis, consists of investigations, including design investigations, into landscape processes. The second component, integration, is the synthesis of knowledge gained from analysis with additional inputs, such as societal values, to develop generalized design pattern rules. The third component, implementation, is the application of the generalized pattern to create place-specific designs that respond to site conditions, stakeholder knowledge and local goals.

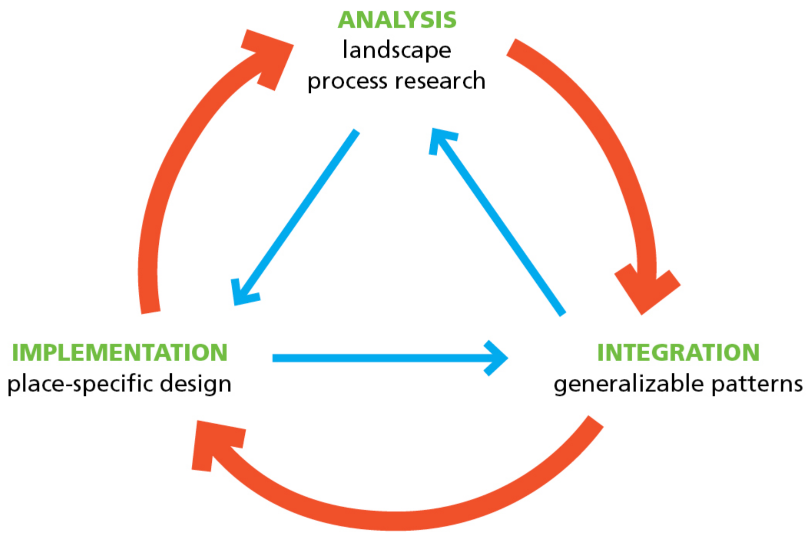


Figure 5. Iterative model of landscape innovation (adapted from Nassauer and Opdam 2008)

This model for landscape innovation achieves its full potential when it is an iterative process with each component feeding back into the model to inform the other two. For example, lessons learned from site-specific implementation can feed back to the integration component, pointing to ways in which the generalized design pattern may need to be altered or expanded. Implementation may similarly feed back to the analysis component highlighting the need for additional research, such as gaining a greater understanding of underlying ecological processes.

In examining the development of RSC, this iterative process of landscape innovation delineated by Nassauer and Opdam is evident. RSC was originally created in the early 2000s for implementation in the coastal plain in Anne Arundel County, Maryland. It was developed by a landscape architect, Keith Underwood, a native of Anne Arundel County, who is very knowledgeable about the landscapes of Anne Arundel County, and passionate about the species and habitat of those landscapes with which he grew up.

Underwood analyzed landscapes such as coastal plain acidic seepage swamps and fall line terrace gravel bogs, freshwater landscapes that are fed by groundwater that seeps through permeable layers of sand and gravel with microtopographies of repeated shallow pools and hummocks (Harrison and Knapp 2010). He also examined the processes of beaver dam landscapes with their repeating sequence of dams and resulting impoundments that modulate stream flow and act as sediment sinks (Butler and Malanson 2005; Wright, Jones, and Flecker 2002).

Underwood synthesized the knowledge gained about the mechanisms of these analogous landscapes through a biomimetic process to create the generalized design pattern of RSC. Biomimicry, the practice of studying patterns, processes and systems in nature and emulating them to solve human problems (Benyus 2002; Kenny et al. 2012), is an innovative approach to achieving sustainable landscape solutions that aligns with the design-in-science paradigm exemplified in Nassauer and Opdam's model (Musacchio 2011).

Figure 6. Analogous landscapes (l–r): Coastal plain seepage swamp, Cecil County, MD (MD DNR); fall line terrace gravel bog, Prince George's County, MD (MD DNR); beaver dam (Biohabitats)

Initial installations of RSC were in the coastal plain in Anne Arundel County, Maryland in the early 2000s. These early place-specific implementations often focused on the creation of habitat for the globally rare Atlantic White Cedar (*Chamaecyparis thyoides*) in addition to stormwater management and water quality (Underwood et al. 2005; Browning 2010). Over the subsequent fifteen years, implementation of RSC has expanded from use in the coastal plain to the piedmont and is now a credited stormwater BMP by the Maryland Department of the Environment (MD DOE 2014) and the EPA Chesapeake Bay Program (WQGIT 2014).

In line with the iterative pattern of Nassauer and Opdam's model, lessons learned from site-specific design implementations of RSC have driven continued innovation. One example is the expansion of the generalized design pattern of RSC to include boulder cascades, which are employed in conjunction with the cobble weirs to allow for greater flexibility for RSC to be implemented on sites with steep slopes (Figure 7). Lessons learned have also led to an evolution of generalized design applications to include conveyance and infiltration of surface drainage, rehabilitation of eroded outfalls, seepage wetlands and in-stream restoration (Cappiella et al. 2008), resulting in the emergence of three main typologies of RSC (H. Flores, McMonigle, and Underwood 2012):

- The *classic RSC* consisting of shallow aquatic pools, riffle weir grade controls, boulder cascades, native vegetation and a porous sand media bed is used to convey and infiltrate surface drainage and to restore eroded outfalls on sites with slopes greater than 5 percent.

- In perennially wet settings with accessible floodplains and slopes of 2 percent or less, the *wetland seepage RSC* employs of a series of riffle grade controls to divert storm flow to the floodplain thereby encouraging wetland areas to establish.
- The *instream riffle RSC* consists of one or more rock riffles placed in an eroded stream channel to encourage upstream sedimentation and reconnection with the adjacent floodplain.

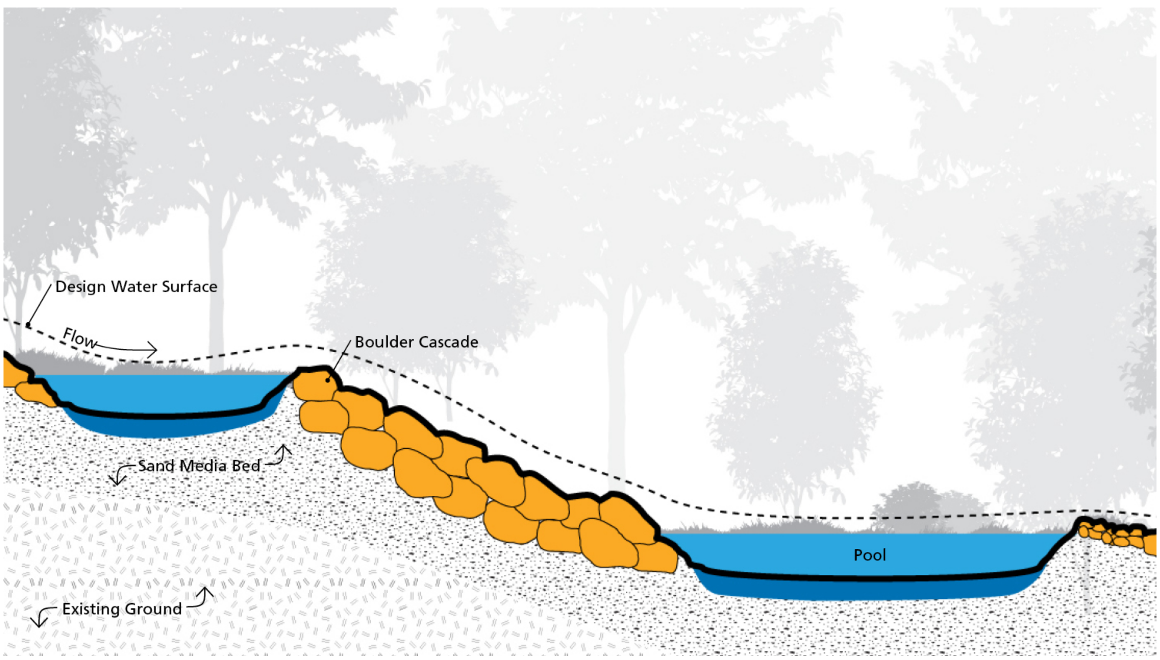


Figure 7. Boulder cascade

Implementations of RSC have also fed back into the analysis component of the landscape innovation model, pointing to the need for further research. RSC has been credited by the Maryland Department of the Environment as a Runoff Reduction BMP since 2011, and it's use as a stormwater BMP is growing. However, the water quality performance of RSC has been largely derived by examining the performance of analogous BMPs, such as bioretention and sand filtration. Though some data is available on the water quality performance of RSC, little of it is peer-reviewed (Filoso and Palmer 2011; Cizek 2014), and the growing implementation of RSC as a stormwater BMP has pointed to the need for targeted research using standard methods (Filoso and Palmer 2009). In 2015, the Chesapeake Bay Trust funded research by the Smithsonian Institution to "measure the removal of nutrients and suspended sediments by Regenerative Stormwater Conveyances (RSC) and relate removal efficiencies to impervious surface in the watershed, and the rate and variability of water inflow (Chesapeake Bay Trust 2015)." The results of this and other focused research on the water quality performance of RSC will provide new knowledge to drive further development and innovation of the RSC system, as well as inform best practices in RSC design. Figure 8 illustrates the development of RSC as an instantiation of Nassauer and Opdam's model of landscape innovation

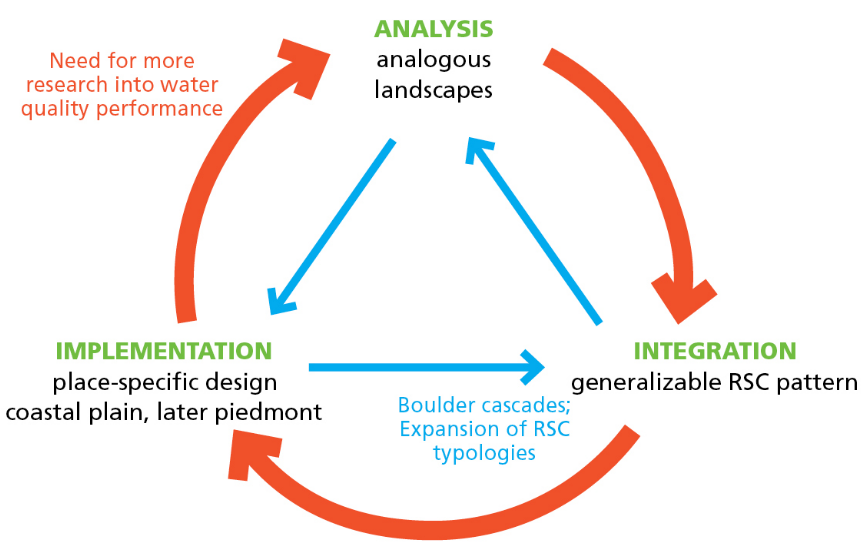


Figure 8. The development of RSC vis a vis the iterative model of landscape innovation

Conclusion

RSC fits into a number of broad theoretical frameworks. It is a designed ecological solution to human-created problems around polluted stormwater runoff. It is a novel ecosystem that provides an alternative stable state in degraded urban contexts, and it is a regenerating system that self-improves through the positive feedback loop created by the interaction of the microbial and plant communities. Developed through a biomimetic process of emulating freshwater seepage landscapes and beaver dams, the creation and continuing evolution of RSC stands as a real instance of Nassauer and Opdam's template of iterative landscape innovation.

CHAPTER 3 Site Selection and Context

The City of Baltimore comprises all or part of four watersheds: the Gwynns Falls, the Jones Falls, the Back River and the Direct Harbor (Figure 9). Each of these watersheds drains to the Chesapeake Bay by way of the Patapsco River, and three of them—Gwynns Falls, Jones Falls and Direct Harbor—drain into Baltimore's Inner Harbor.

The project site is a 2.3 acre (0.9 ha) catchment located in central Baltimore City in the Jones Falls Watershed, a 40 square mile (104 square kilometer) watershed with headwaters in rural Baltimore County. Of the approximately 200,000 residents living in the Jones Falls Watershed, 130,000 live in Baltimore City (Mussman 2016).

The project is on a hilltop adjacent the Stoney Run stream valley where a poorly functioning impervious drainage channel partially captures the stormwater runoff from the site, sending it directly into the stream. Extensive maintenance work has been done on water and sewer utilities located in the stream valley, and the Stoney Run stream is also undergoing restoration.

Approximately a quarter of a mile downstream from the site, the Stoney Run enters a pipe before it merges with the Jones Falls River; which empties into Baltimore's Inner Harbor. Baltimore Harbor Water Alert, a project run by Baltimore's watershed organization, Blue Water Baltimore, monitors a water quality station located downstream from the site near where the Stoney Run goes underground ("Stoney Run Station" 2016).

Figure 9. Case demonstration watershed context

Stormwater Management in the City of Baltimore

Like many cities, Baltimore has an aging and outdated storm sewer system designed in the "sanitary city" model of the early 20th century as a response to the hazards of rapid urban industrialization. Engineered to remove stormwater runoff from the city streets and into receiving streams and the harbor quickly as possible, this stormwater strategy was highly successful in terms of mitigating the public health risks associated with allowing stormwater to stagnate in place (Baltimore Ecosystem Study 2013). Over time, however, the environmental consequences arising out of this strategy have become apparent as pollutants and nutrients are efficiently transported to the harbor, and ultimately the Chesapeake Bay, along with the stormwater.

Built in 1905, Baltimore's storm sewer system was designed to handle stormwater runoff from far less impervious surface than exists in the city today. Though Baltimore's sanitary and storm sewers are separate, they run adjacent to one another (Boone 2003), and during large precipitation events storm sewers can become overburdened allowing water to seep through cracks in the sanitary sewers, creating sewage overflows out of manholes and relief valves that empty directly into urban streams (Wheeler 2015). As a result of these sanitary sewer overflows (SSOs), in 2002 Baltimore's wastewater utility was placed under a consent decree (CD) with the United States EPA, the Maryland Department of the Environment (MDE) and the Department of Justice to bring the wastewater collection system into compliance with the Clean Water Act by January 1, 2016 (Pelletier and Qadri 2014; Chow et al. 2014). Baltimore City has missed this deadline, completing only 31 of the 54 projects outlined in the CD and is now in negotiations with EPA and the MDE to develop a new deadline, possibly as late as 2019, to complete the requirements of the CD (Gilbeau 2016).

Baltimore's Healthy Harbor Initiative

In 2010, the U.S. EPA under a Clean Water Act mandate issued total maximum daily loads (TMDLs) for nutrient and sediment pollution in the Baltimore Harbor, Patapsco River and the entire Chesapeake Bay Watershed (US EPA 2010). Concurrently, the non-profit Waterfront Partnership of Baltimore launched the Healthy Harbor Initiative seeking to make Baltimore Harbor safe for swimming and fishing by 2020. Improved stormwater management is a critical component of this 10-year strategic plan which calls for a 10 percent reduction in nutrient loads and a 10,000 ton-per-year reduction in sediment loads in stormwater runoff from urban impervious cover by 2020. The plan further seeks to install green infrastructure to the maximum extent practical to treat runoff from impervious cover with a target of treating 6 percent of existing impervious cover by 2020, and 16 percent by 2040 (Complete Healthy Harbor Plan 2011).

Baltimore Harbor's Water Quality Status Today

Each summer Baltimore's non-profit watershed association, Blue Water Baltimore, issues a Healthy Harbor Report Card as a means of tracking progress toward the goal of a fishable, swimmable harbor by 2020. While the most recent report—issued in 2015 for 2014 data—found some areas of improvement, the overall Baltimore Harbor health grade was an F, with the Inner Harbor Basin receiving a D-minus. Water quality in the Jones Falls Watershed was worse in 2014 than it had been in 2013, receiving a grade of F; the Stoney Run stream also received a grade of F (Blue Water Baltimore 2015).

The water quality data that informs the Healthy Harbor Report Card is collected by the Ambient Water Quality Monitoring Program of Blue Water Baltimore. The monitoring program samples 22 locations on the Tidal Patapsco River and 27 locations in the Jones Falls and Gwynns Falls Watersheds, including a monitoring station on the Stoney Run stream approximately a quarter mile downstream from the project site. The most recent measurements from the Stoney Run Station (Figure 10), taken on January 12, 2016, detected unhealthy levels of fecal bacteria (500 colonies/100mL), total nitrogen (2.4 mg/L) and total phosphorous (0.019 mg/L). Turbidity, which indicates levels of suspended solids such as algae and sediment, was below the State of Maryland's established numeric threshold of 150 NTU for ecological health of freshwater streams ("Stoney Run Station" 2016).

Figure 10. Stoney Run Station Water Quality Measurements, January 12, 2016 (harboraltert.org)

The Potential Role for RSC in Baltimore City

Urban stormwater runoff is a significant and growing pollution source of concern (Koch et al. 2015; Cizek and Hunt 2013), as the increase of impervious surfaces brought about by the process of urbanization alters hydrology resulting in increased surface stormwater flow (Shuster et al. 2005). As an approach that offers both runoff reduction and water quality benefits, RSC fits into the larger resiliency framework (Novotny, Ahern, and

Brown 2010) that Baltimore seeks to employ as a means transforming itself into a sustainable city (Baltimore Commission on Sustainability 2009). Enhancing upland stormwater infrastructure is known to induce hydrological changes that help cleanse polluted runoff, reducing nutrients and sediments before it reaches a stream (Filoso and Palmer 2011). RSC aligns with the principles of Green Infrastructure (Benedict and McMahon 2006), Low Impact Development (LID) (US EPA 2000; Collett, Friedmann, and Miller 2013) and Environmental Site Design (ESD) (MD DOE 2009), and it provides a stormwater management practice that combines features and benefits of other stormwater BMPs such as swales and bioretention (Brown, Berg, and Underwood 2010). The general design pattern of RSC is adaptable for site-specific design requirements, and installation of RSC is possible within a constrained area of disturbance, making it especially suited to urban settings where space is limited (Brown, Berg, and Underwood 2010; Berg 2009). The opportunity for stakeholder education, participation and stewardship—as well as biodiversity, habitat, aesthetic and recreation benefits—makes RSC an excellent candidate for a multifunctional urban stormwater landscape amenity.

Why This Site?

This case demonstration investigates the potential of implementing RSC in the City of Baltimore as an innovative Green Infrastructure strategy for landscape architects and other designers addressing stormwater issues. The site was chosen for a number of reasons. The existing engineered stormwater system functions poorly, only partially capturing the stormwater runoff from the site and offering no benefits beyond conveyance. Thus there is an excellent opportunity to retrofit a poorly working, singlefunction stormwater system, expand the drainage area being captured and treated, and transform a waste product—stormwater runoff—into a multifunctional amenity landscape with ecological, economic and cultural benefits (Batten and Rottle 2011). Further, located at the nexus of multiple walking-oriented neighborhoods and adjacent to an access point to a popular local wooded trail, the site is encountered regularly by numerous residents and visitors. Geographer Alan Pred (1990) has coined the term "daily path" to signify the primacy of such landscapes that are experienced as part of ordinary life and which have the capacity to shape and influence cultural norms (Mozingo 1997).

Finally, the site's urban location affords an occasion to create a research opportunity examining RSC performance as a Green Infrastructure practice in an urban context. Potential partners for such research include the nearby Johns Hopkins University and the Baltimore Ecosystem Study among others.

CHAPTER 4 Precedents

The following precedents showcase a range of RSC implementations in urbanized environments. The Cabin Branch RSC in Anne Arundel County, Maryland, is a far larger project than the case demonstration that is the focus of this thesis. However, it is an instructive precedent as it is located in an urbanized area and it showcases the flexibility of RSC as a stormwater mitigation strategy. The Brier Mill Run RSC in Prince George's County, Maryland, is a recently installed project that, like the case demonstration, is a site with steep slopes. The Cypress Beach RSC in Anne Arundel County, Maryland, is a small site retrofit of an impervious drainage, similar to the case demonstration site.

Cabin Branch RSC, Anne Arundel County, Maryland

Constructed in 2012–2013, the 1700 linear foot (518 m) Cabin Branch RSC in Anne Arundel County treats a 144 acre (58 ha) catchment in a highly urbanized area near a major shopping mall, warehouse club and light industrial development in the Saltworks Creek watershed of the Severn River. Though it is a much larger project than the Baltimore City case demonstration, and in the coastal plain physiographic region of Maryland, it serves an instructive as a precedent due to its highly urbanized location and its demonstration of the flexibility of RSC. The RSC comprises three reaches that demonstrate the typological variability of RSC: An eroded outfall RSC, an upland stormwater retrofit RSC and a sand seepage wetland complex RSC.

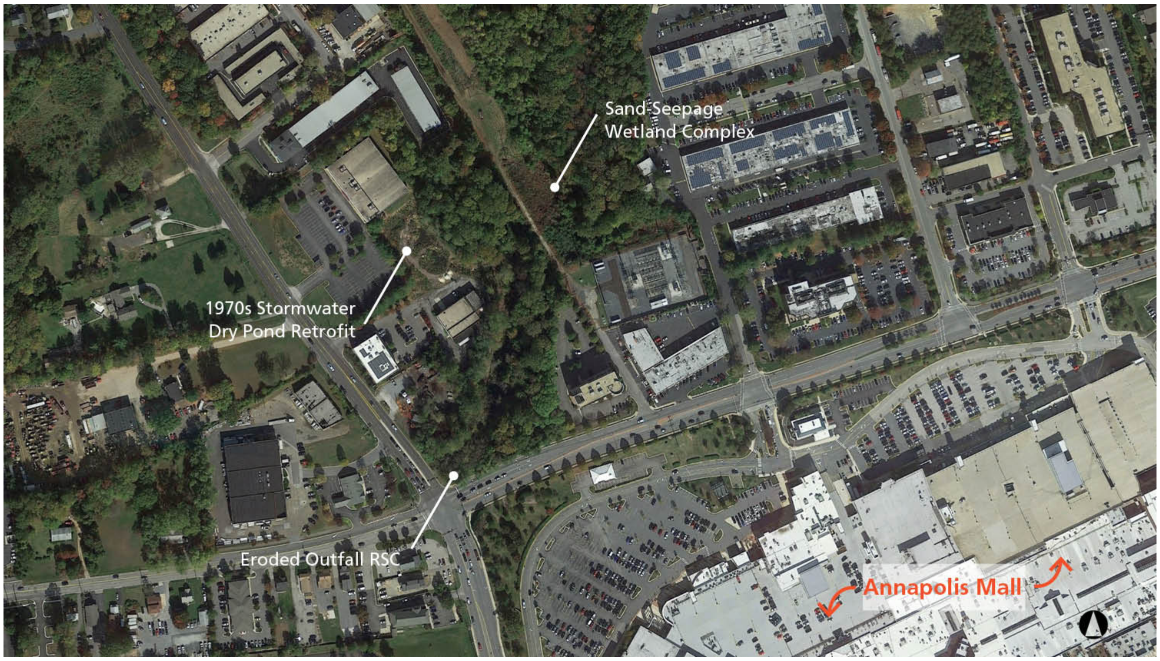


Figure 11. Aerial view of the Cabin Branch RSC site, Anne Arundel County, Maryland (Google Earth)

Eroded Outfall RSC. The first reach of the Cabin Branch RSC is the restoration of an eroded stormwater pipe outfall at the northeast corner of the intersection of Generals Highway and Bestgate Road. The gully that had eroded as a result of this outfall has been restored into a system of vegetated pools, riffle weirs and boulder cascades that flows through a valley to the sand seepage wetland RSC.

Figure 12. Eroded outfall RSC before (left) and after (right) restoration (Underwood & Associates)

Upland Stormwater Retrofit RSC. The second reach of the Cabin Branch RSC is a retrofit of a 1970s stormwater dry pond. The pond, which had been identified by Anne Arundel County Watershed's Implementation Plan as in need of updating to contemporary practices, was filled to the level of the adjacent parking lot and reformed to capture stormwater and channel it to a series of pools, riffle weirs and cascades which merge with the first reach of the RSC just above the sand seepage wetland RSC.


Figure 13. Upland stormwater retrofit RSC before (left) and after (right) restoration (Underwood & Associates)

Sand Seepage Wetland Complex RSC. The third of the Cabin Branch RSC receives the flow from the first two reaches, and it is located furthest down the stream valley in an area with shallow slopes. The existing entrenched stream was raised and riffle weirs and sand berms were installed to reconnect the stream with the surrounding floodplain. The result is a series of threaded stream channels with a wetland complex.

Figure 14. Sand seepage wetland complex RSC before (left) and after (right) restoration (Underwood & Associates)

The project removed invasive and reintroduced native plant species to the stream valley and forested wetland by planting over 2500 plants in total, including 500 globally rare Atlantic White Cedar (*Chamaecyparis thyoides*). Volunteers from diverse groups from school children to watershed supporters to Maryland Department of Natural Resources employees were involved in the installation of the project. The Cabin Branch RSC continues to provide a resource for research and for professionals to learn about the techniques of RSC. (Severn Riverkeeper 2013; Chesapeake Stormwater Network 2014)

Brier Mill Run, Prince George's County, Maryland

Figure 15. Brier Mill Run RSC before (left) and after (right) restoration (Biohabitats, left, and the author)

The Brier Mill Run RSC is a project of the Anacostia Watershed Society that was constructed in the fall of 2015. The site is at the outfall of a 3 foot (1 m) diameter pipe that drains an approximately 50 acre (20 ha) catchment. The outfall is located behind the William Wirt Middle School in Riverdale Park, Prince George's County, Maryland. Stormwater runoff emerging from the outfall had eroded the hill slope leading down to the Brier Mill Run stream, undercutting and damaging the outfall structure itself and creating a hazard to students using the school's adjacent ball fields (Figure 15). At 125 feet (38 m) long with an average slope of 9.5 percent, the Brier Mill Run RSC is similar to the case demonstration site in that it has a relatively short reach that traverses a steep slope. (Peter May, personal communication, April 15, 2016)

Cypress Beach RSC, Anne Arundel County, Maryland

Figure 16. Cypress Beach RSC before (left) and after (right) restoration (Anne Arundel County Department of Public Works)

The Cypress Beach RSC in the Manhattan Beach community in Anne Arundel County, Maryland is a 2010 retrofit of an impervious drainage ditch that drained the surrounding neighborhood's stormwater runoff directly onto the community's swimming beach and into the Magothy River. Though on the coastal plain physiographic region of Maryland, it is relevant to the case demonstration because of the small scale of the site. An approximately 30 foot (9 m) by 150 foot (46 m) street-end park was restored as a RSC designed to convey the 100 year storm peak volume and capture and treat up to 3.2 inches (8.1 cm) of rainfall from a 10 acre (4 ha) drainage. The site's suitability for a RSC retrofit was reinforced when evidence of peat from a historic magnolia bog was discovered during a site visit. The local civic association was an enthusiastic partner in the project, and numerous volunteers aided in the planting of emergent grasses (*Spartina spp*.) on the beach and native vegetation across the RSC system, including Sweetbay

Magnolia (*Magnolia virginiana*), Pitch Pine (*Pinus rigida*), Summersweet (*Clethra alnifolia*), Swamp azalea *(Rhododendron viscosum*) American Cranberry (*Viburnum trilobum*) and Blue flag iris (*Iris versicolor*). The installation process was documented in a video posted on YouTube to inform and encourage similar projects, and signage explaining the concept and benefits of the project was posted on the site. Post installation, the majority of storm events result in no outflow from the RSC (i.e., 100 percent infiltration), and larger events, including Hurricane Irene and Tropical Storm Lee, result in a reduced peak discharge from the RSC that is less than the peak inflow. (H. E. Flores et al. 2012; *Manhattan Beach Coastal Plain Outfall* 2011)

CHAPTER 5 Site Analysis

Neighborhood Context

The project site is located in central Baltimore City at the nexus of the Hampden, Remington and Wyman Park neighborhoods. It is contained within a linear City-owned park, also called Wyman Park, which encloses the Stoney Run stream valley. A popular wooded trail, known variously as the Stoney Run Path and the Ma & Pa Trail, follows the Stoney Run along the former right of way of the narrow gauge Maryland and Pennsylvania (Ma & Pa) Railroad that ran from Baltimore to York, Pennsylvania until the late 1950s. The project site is one of only two access points to the Stoney Run path along the lower reach where the stream valley is very steep. The area is highly walkable with an average Walk Score® of 91 according to the public access walkability index by the private Walk Score company that measures pedestrian friendliness ("Walk Score Methodology" 2016). There are a number of destinations within half of a mile of the site, including the Johns Hopkins University, the Baltimore Museum of Art, two K–8 schools, Hampden Elementary/Middle School and the parent co-operative GreenMount School, and a thriving commercial hub on West 36th Street (locally known as "the avenue").

Figure 17. Neighborhood context and circulation

Demographics

In 2010 the neighborhoods of Hampden, Remington and Wyman Park had a combined population of 10,562 with a median household income of $60,104 (BNIA-JFI 2015). The population of the area is predominantly white (77.2%), with a racial diversity index of 40%. A majority of residents are between the ages of 25 and 64, and slightly more than half have at least a bachelor's degree, perhaps reflective of the proximity of Johns Hopkins University.

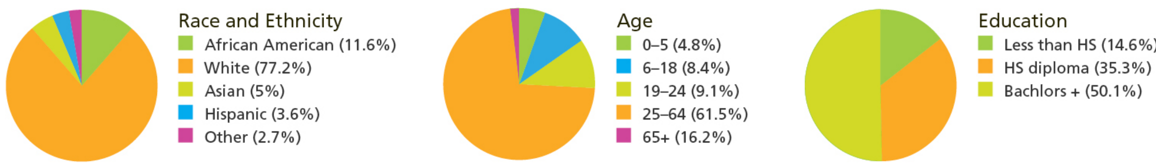


Figure 18. Hampden–Remington–Wyman Park demographics (bnia-jfi 2015)

Existing Conditions

The site is located to the immediate west of the Stoney Run where West 33rd Street turns to the southeast and becomes Remington Avenue (Figure 19**Error! Reference source not found.**). The main 1.7 acre (0.7 ha) drainage area is drained by an open concrete channel that leads from an alley behind rowhouses on the site and terminates in a storm sewer inlet. A second 0.6 acre (0.2 ha) drainage area consists mostly of the road right of way and terminates in a storm sewer inlet along the curb. During large precipitation events, however, fast-moving stormwater runoff bypasses this inlet, ponding in a low point on the bridge over the Stoney Run stream and flowing over the side of the bridge causing erosion and infrastructure damage. An asphalt road leading down into the stream valley provides pedestrian access to the Stoney Run path as well as maintenance access to storm sewer infrastructure, however the road is in severe disrepair.

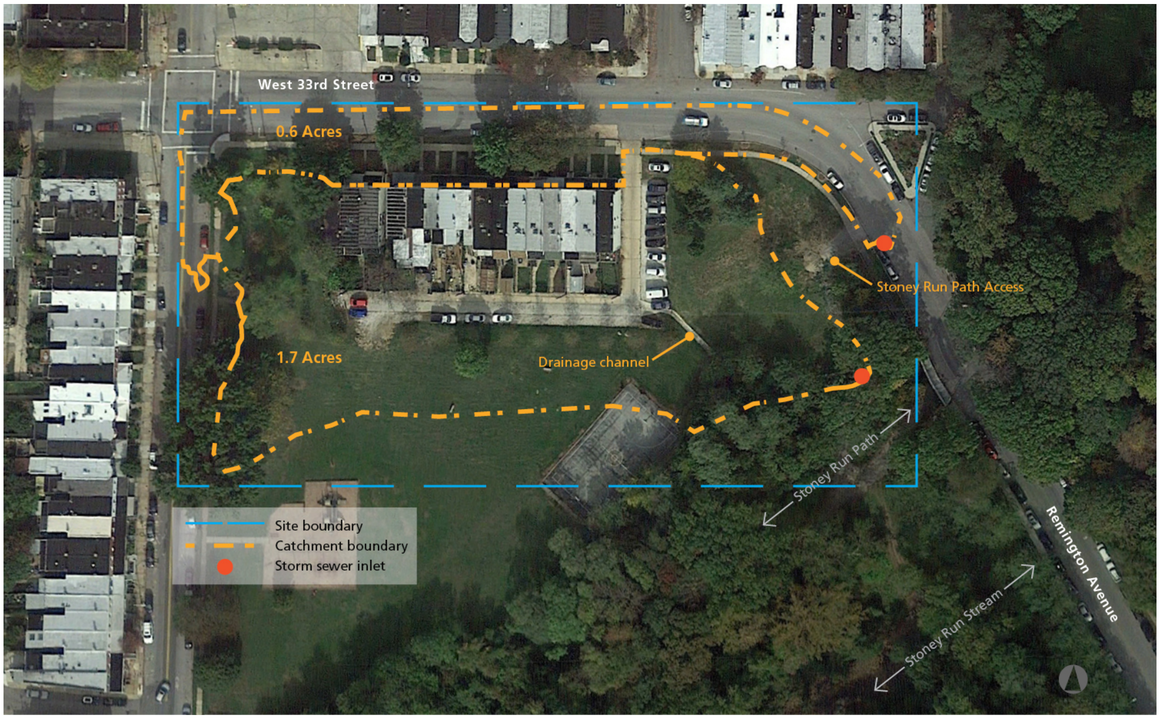


Figure 19. Existing conditions—drainage areas

Figures XX–XX provide a visual inventory of existing site conditions. The existing concrete channel that drains the larger catchment on the site is shown in Figure 20. At the start of the system, where the alley behind the rowhouses meets the channel (top left image), runoff bypasses the system is causing erosion. The top right image shows the channel further down the hill slope, and the storm sewer inlet structure is shown in the bottom left image. At the terminus of the system, runoff short circuits the engineered structure and causes erosion further down the hill, as seen bottom right and in greater detail in Figure 21.

Figure 20. Existing conditions—concrete drainage channel

The images in Figure 21 further illustrate the damage resulting from the runoff that short circuits the concrete drainage channel system. The left image shows erosion and undercutting to the inlet structure itself, and the right image shows the condition of the asphalt access road below the storm sewer inlet structure where unchecked erosion has caused severe deterioration.

Figure 21. Existing conditions—storm sewer inlet structure and asphalt road

The images in Figure 22 are outside the bounds of the project site itself, but they illustrate the results of the poorly performing systems on the site. The left image, taken from the near the Stoney Run stream, looks up to the low point on the Remington Avenue bridge where stormwater that bypasses the curbside storm drain ponds and flows over the side of the bridge. The Baltimore City Department of Public Works has attempted to mitigate the damage by armoring the hillslope, but continuing erosion is clearly evident to the right of the riprap. Left unabated, this condition will ultimately result in severe damage to the bridge infrastructure. The two right-hand images show the Stoney Run stream itself during baseflow and storm flow conditions.

Figure 22. Existing conditions—Remington Avenue bridge and Stoney Run stream

Hydrology

The primary catchment on the site is a 1.7 acre (0.7 ha) drainage encompassing a row of houses on the south side of 33rd Street and a portion of the open space behind the houses. The catchment has 40 percent impervious surfaces and a peak flow rate for the 100-year storm of 7.9 cfs (0.22 cms). Stormwater runoff in this drainage area flows into the alley behind the houses, thence to the concrete drainage channel down the hillslope to the storm drain inlet. Part of the runoff, however, escapes this system causing erosion both at the top of the concrete channel and at the inlet structure.

The second catchment on the site drains a portion of the road right of way and the front yards of the houses. This 0.6 acre (0.2 ha) drainage has a peak flow rate for the 100-year storm of 6.56 cfs (0.19 cms). The stormwater runoff in this catchment concentrates quickly in the gutter and enters into a storm sewer at the curb. The stormwater velocity, however, is such that during larger precipitation events runoff bypasses the storm sewer inlet, ponding in a low point on the Remington Avenue bridge above the Stoney Run stream, flowing over the edge, and causing erosion and damage to the bridge infrastructure.

The stormwater runoff captured by the two storm sewer inlets on the site flows in pipes to an invert located downslope below the Stoney Run path, and from there it outfalls directly into the Stoney Run stream without any flow attenuation or water quality treatment. Additionally, a portion of the site is unmanaged by either of the existing drainage systems. Stormwater runoff in this are flows down the asphalt access road causing significant damage.

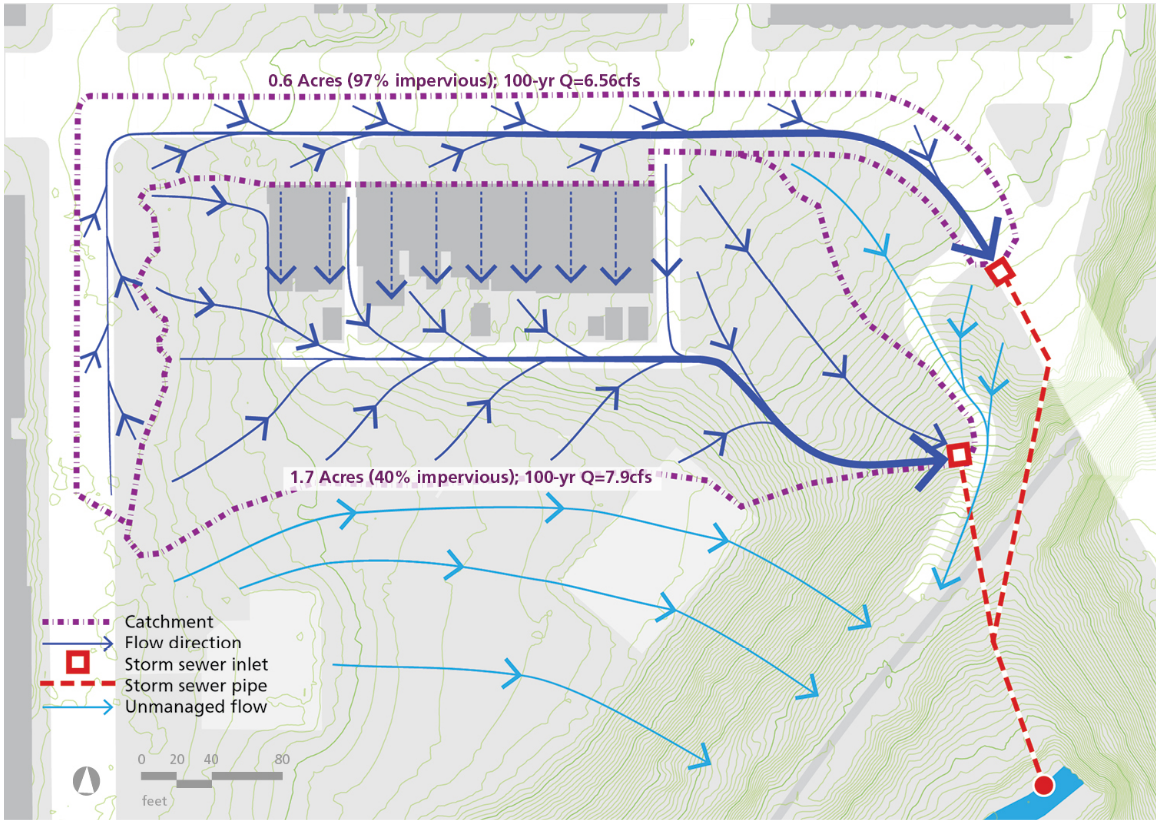


Figure 23. Existing conditions—hydrology

Slopes and Soils

The slopes analysis shows that the site is a bluff-like condition, with shallow slopes rapidly becoming quite steep (25+ percent) at the edge of the stream valley. The existing concrete drainage channel on the site is 185 feet (56 m) long with an average slope of 12.8 percent. All soils on the site are Hydrologic Soil Group A, non-hydric and well drained, with a depth to water table of greater than 80 inches ("NRCS Web Soil Survey" 2016).

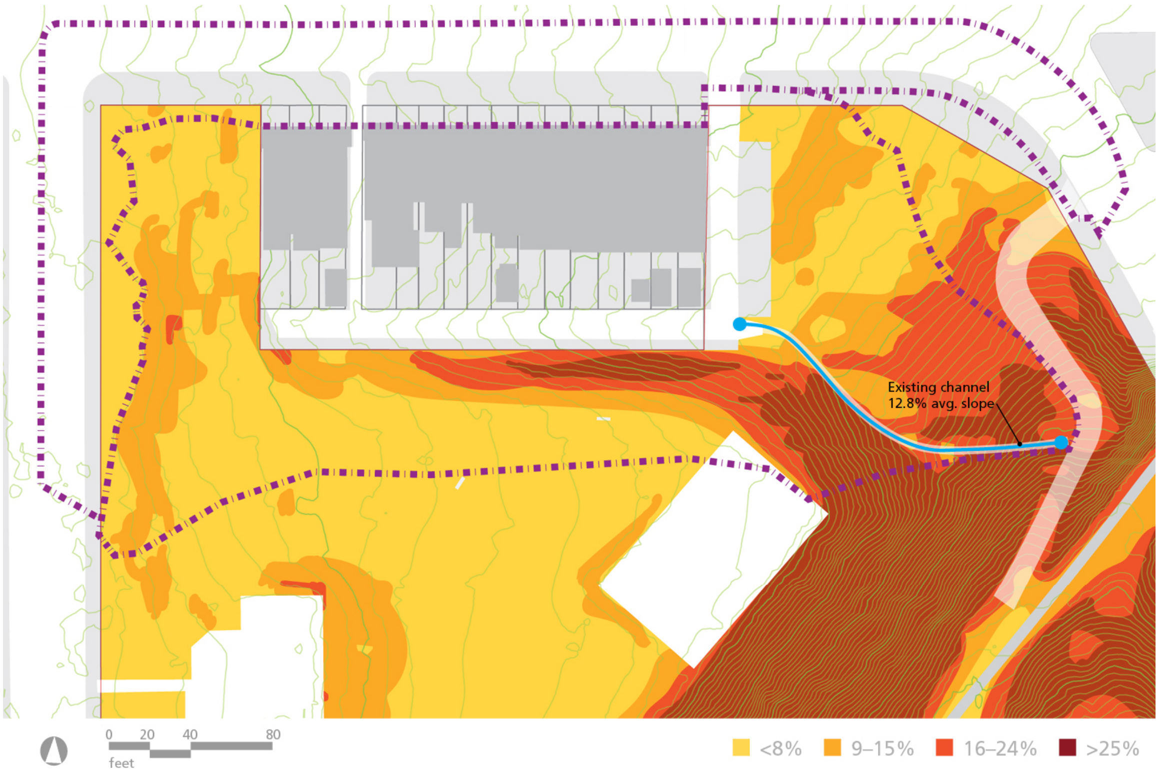


Figure 24. Existing conditions—slopes

Land Cover

The existing land cover is predominantly open turf interspersed with mostly deciduous trees and two small gravel areas for parking to the east and the south of the rowhomes. Two large willow oaks (*Quercus phellos*) at the very west of the site near the play area of the park are the oldest trees on the site. Additional species include additional oaks (Quercus spp.), Red maple (*Acer rubrum*), Eastern redbud (*Cercis Canadensis*), Goldenrain tree (*Koelruteria paniculata*) and two Eastern white pines (*Pinus strobus*). The stream valley is heavily wooded, but also rife with invasive species, particularly vines such as porcelainberry (*Ampelopsis brevipedunculata*), English ivy (*Hedera helix*), poison ivy (*Toxicodendron radicans*), Oriental bittersweet (*Celastrus orbiculatus*), and Japanese honeysuckle (*Lonicera japonica*).

Figure 25. Existing conditions—land cover

CHAPTER 6 The Case Demonstration

This case demonstration proposes to retrofit a poorly functioning concrete drainage channel in a small catchment in Baltimore City, thereby implementing RSC in a new context and expanding the Green Infrastructure "toolkit" for use in Baltimore City. This chapter first discusses the ecological, sociocultural and economic goals that emerged as a response to the site inventory and analysis and then outlines the design proposal.

Goals

Ecological Goals

- Convey the peak runoff volume (Q) from the 100-year storm
- Capture and treat 1.0 inch (2.54 cm) of rainfall, thereby reducing nonpoint source pollution runoff
- Establish a stable piedmont plant community with focus on native species and climate change resiliency
- Expand tree canopy
- Remove invasive species

The first goal, to convey the peak runoff volume from the 100-year storm, is the conveyance performance standard for RSC. To check that the proposed design meets this standard, the hydrology of the proposed drainage area is modeled using the USDA Natural Resource Conservation Service's Win TR-55 Watershed Hydrology software to determine the 100-year storm peak flow rate; next, the maximum flow capacity of the proposed RSC is calculated using Manning's formula; and, finally, the two sets of numbers compared. The maximum flow capacity number must be equal to or greater than the TR-55 numbers to meet the 100-year conveyance goal.

The water quality goal for the project is to capture and treat 1.0 inch (2.54 cm) of rainfall. To check that the proposed design meets this goal, the storage volume of the proposed RSC in both the pools and the void spaces is calculated in acre feet (cubic meters). The result is then entered into a standard stormwater retrofit equation (WQGIT 2014) to determine inches (centimeters) of rainfall being treated by the system. Finally, pollutant removal curves for stormwater retrofit practices (WQGIT 2012) are consulted to determine pollution removal quantities for total nitrogen, total phosphorus and total suspended solids.

A critical component of RSC is the establishment of a native plant community appropriate to the site-specific conditions. The project is located in the piedmont physiographic region of Maryland, close to the fall line where the piedmont plateau gives way to the coastal plain. The vegetation goal of the project is to establish an appropriate native piedmont plant community following ecological planting strategies (Beck 2013; Ranier and West 2015) that anticipates for climate impacts (Hunter 2011) and greatly expands the tree canopy.

Sociocultural Goals

- Create an opportunity for residents to engage with RSC as part of their "daily path"

- Create a "gateway" marking the entrance into Hampden and the access to the Stoney Run path
- Create a research opportunity examining RSC performance as a Green Infrastructure practice in an urban context
- Create opportunities education and stewardship

Geographer Alan Pred (Pred 1990) has coined the term "daily path" for the landscapes one experiences as part of ordinary life. These landscapes reflect the relationship between social and spatial structures, and as such they have the ability to influence cultural norms (Mozingo 1997). Creating an opportunity for residents to engage with a RSC landscape as part of their daily path establishes a circumstance whereby they may shift their perception from one of stormwater runoff as a waste product to seeing it as an amenity and a resource for driving desired ecosystem services (Batten and Rottle 2011; Termorshuizen and Opdam 2009).

As discussed previously, the project site is located at the nexus of the Hampden, Remington and Wyman Park neighborhoods. It is one of only two access points to the lower reach of the Stoney Run path, and it is also a major portal into the Hampden neighborhood from Remington, the Johns Hopkins University and other neighborhoods east of the park. The existing site, however, fails to celebrate this distinction. It is a bland turf open space without particular identity or function, and the access road down to the Stoney Run path is badly degraded. Over the past few years, the local neighborhood association has attempted to improve the streetscape at this portal by renovating a median into a mini-park across the street from the project site. The sidewalks on The Triangle, as the park is called, were improved and new plantings were installed. In October of 2015, a

14 foot (4.2 m) kinetic metal and glass sculpture by local artist Steve Baker was added to the median giving the entrance into the neighborhood even greater presence (Feldman 2015). The RSC landscape proposed for the site seeks to further reinforce this area as a prominent gateway into Hampden and also highlight the presence of the access to the Stoney Run path.

The project also seeks to create research, education and stewardship opportunities. The case demonstration offers an excellent opportunity for research on the performance of RSC in an urban area. Possible partners for such research include the Johns Hopkins University and the Baltimore Ecosystem Study, among others. Two K–8 schools within a half-mile (0.8 km) of the site create an opportunity for incorporating the site into the environmental education curricula of the schools. Finally, there is an opportunity for volunteer participation and stewardship from the neighborhood associations and the Friends of Stoney Run advocacy group who plan a very active role in the maintenance of Wyman Park and the Stoney Run path.

Economic Goals

- Quantify RSC ecosystem services value
- Quantify expanded tree canopy value
- Contribute toward reducing city budget liabilities stemming from TMDL noncompliance
- Reduce burden on stormwater sewer system and streams
- Increase lifespan of Remington Avenue bridge infrastructure

Economic goals for this case demonstrating include quantifying both the ecosystem services value of the proposed RSC and the ecosystem services value of the proposed expanded tree canopy. A previous researcher (Cizek 2014) has quantified the economic value of the ecosystem services of RSC systems, establishing a value range per hectare of drainage area treated. This value range will be applied to the case demonstration to estimate a range of economic value of the proposed RSC. The ecosystem services value of the proposed expanded tree canopy will be estimates using the USDA Forest Service's peer-reviewed iTree software.

Additional economic goals include helping to reduce city budget liabilities stemming from TMDL noncompliance, reducing the burden on Baltimore's storm sewer system and streams, and increasing the lifespan of Remington Avenue bridge over the Stoney Run stream. While these goals are more difficult to specifically quantify, the water quality calculations showing the volumes of pollutant removals will provide an indicator of the proposed RSCs contribution to achieving Baltimore City's TMDL goals. Similarly, both the water quantity (conveyance) and water quality (capture and treatment) calculations will provide an indicator of how the proposed RSC will lessen the burden on the storm sewer systems and Stoney Run stream. Finally, the design proposal, by redirecting stormwater from the road into the proposed RSC, will directly address the water ponding issue on the Remington Avenue bridge thereby diminishing the damage being caused to the bridge infrastructure.

The Design Proposal

The design proposal calls for a modified drainage area of 2.76 acres (1.1 ha) with three subareas: the "houses" subarea (1.65 acres, 0.7 ha), the "road" subarea (0.6 acres, 0.24 ha) and the "joint" subarea (0.41 acres, 0.17 ha). The entire proposed drainage area is treated by a proposed RSC. The diagram in Figure 26 shows the relationship between the drainage subareas and the reaches of the RSC.

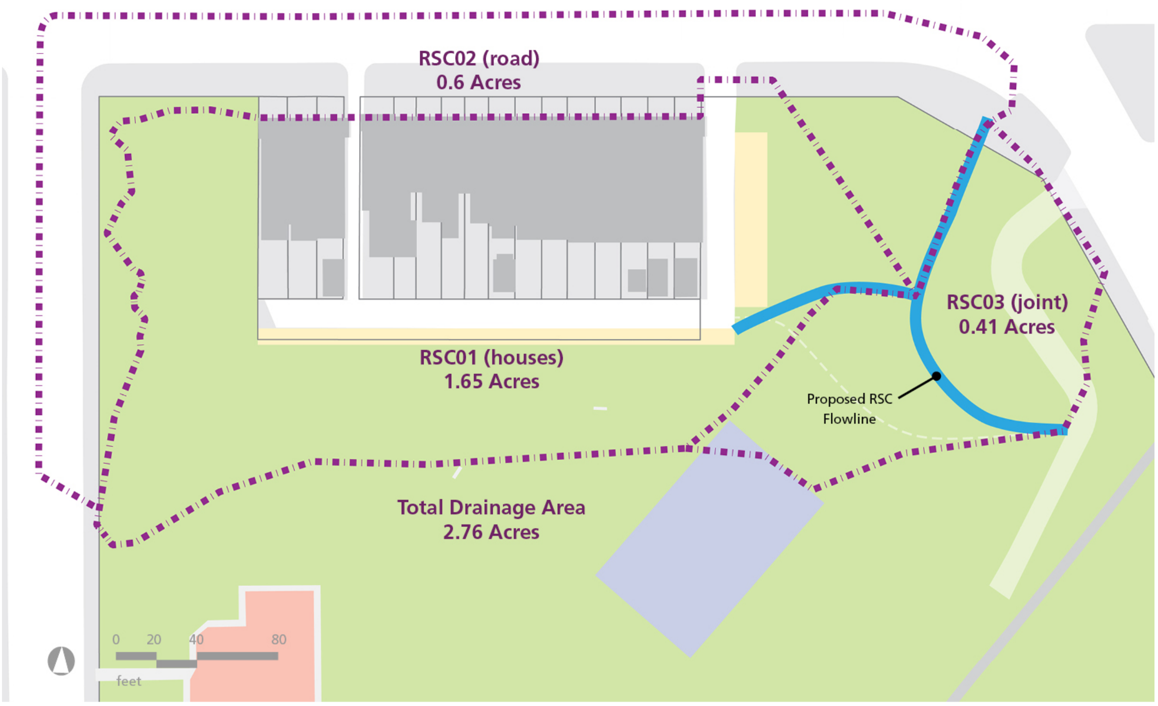


Figure 26. Proposed modified catchment and RSC flowline

The original intention of the case demonstration had been a direct retrofit of the existing concrete drainage channel on the site with a RSC system following the same flowline. However, during the analysis of the existing hydrological conditions of the site the second existing drainage area along the road was discovered, as was the area of the site that currently fails to be captured by either existing drainage area and flows unmanaged down the access road to the Stoney Run path. This presented an opportunity to multiply the benefit of the proposed retrofit by modifying the drainage area and establishing a new flowline for the RSC. A number of trial flowlines were investigated before arriving at the final RSC alignment (Figure 27). The ultimate flowline of the RSC was chosen because it allows the two topmost reaches of the RSC that capture the majority of the stormwater from the site to take advantage of the shallower slopes on the bluff above the stream valley, thereby reducing flow velocity and encouraging greater infiltration of stormwater.

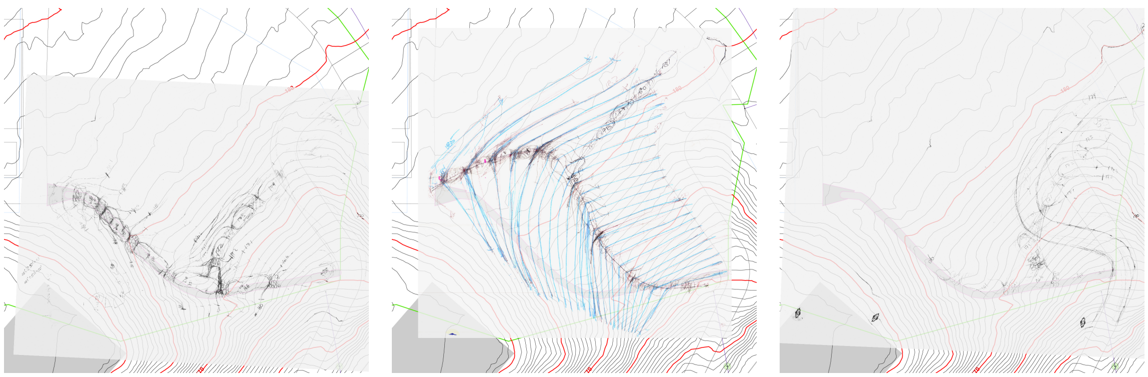


Figure 27. Trial flowline investigations

The rough grading plan in Figure 29 shows how the proposed RSC fits into the landscape. The pools throughout are 2 feet (0.6 m) deep. The two topmost reaches have 5 percent average slopes with 1 foot (0.3 m) elevation change between the surface water elevation in each pool set by cobble weirs. The lower reach of the RSC has a 15 percent average slope with each pool separated by a boulder cascade. Figure 29 shows the typical cross sections of the cobble weirs and pools. The weirs throughout the system are 8 feet (2.4 m) wide and 0.8 feet (0.24 m) deep, the porous media bed is 1.5 feet (0.5 m) deep, and the pools are a minimum of 8 feet (2.4 m) wide.

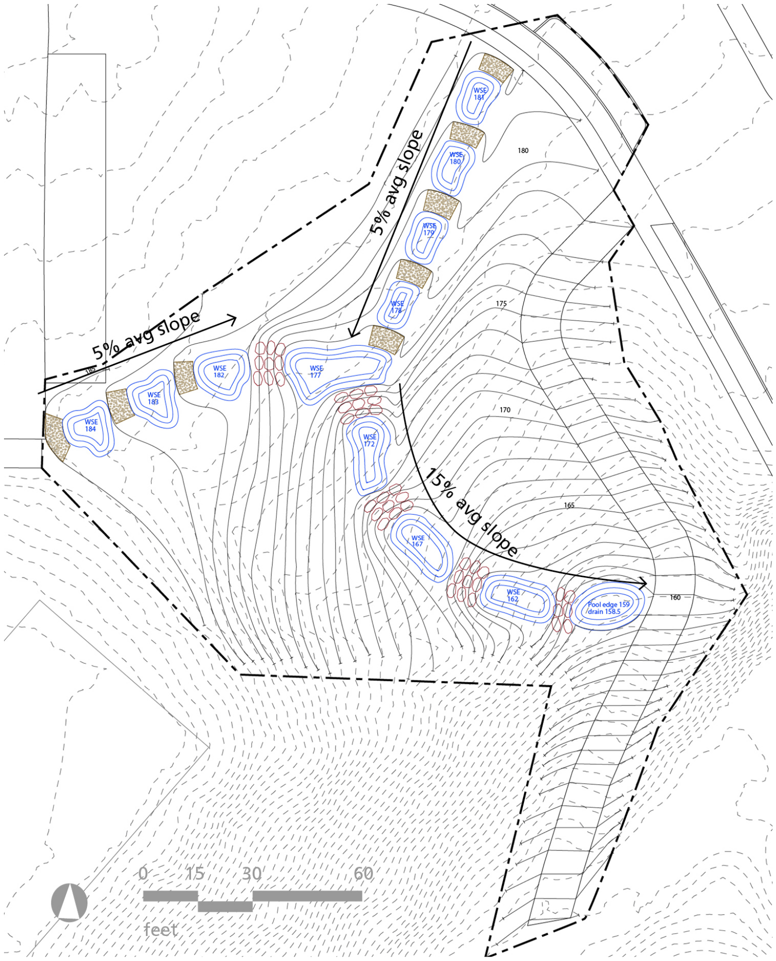


Figure 28. Rough grading plan with 1 foot contours

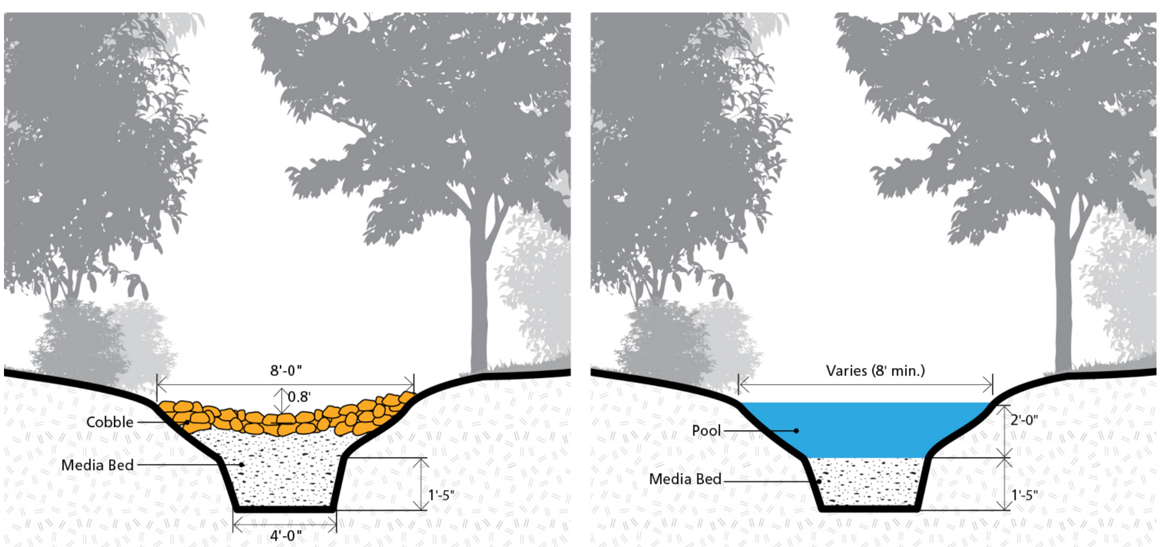


Figure 29. Typical cross sections

The illustrative plan enlargement in Figure 30 reveals more detail about the proposed design. The first reach of the RSC, from the houses subarea, originates in the same location as the existing concrete drainage channel at the southeast corner of the alley behind the rowhouses. The stormwater runoff in the reach will flow toward a central pool along a series of riffle weirs and pools, with a boulder cascade before reaching the central pool. A proposed curb bump out will bring stormwater runoff along the gutter of 33rd Street onto the site and flow along the second reach of the RSC to the same central pool. This reach flows at a gentle 5 percent with a series of riffle weirs and pools. From the central pool, the combined runoff flows along the third reach of the RSC down steeper slopes of 15 percent navigated by a series of pools and boulder cascades. The final reach terminates in the location of the existing storm sewer inlet. This infrastructure will be repurposed as an overflow drain for the RSC system.

The access road into the Stoney Run stream valley remains in improved form to continue to allow both pedestrian access to the Stoney Run path and maintenance access. Secondary paths allow for closer exploration and interaction with the RSC system. The tree canopy has been expanded across the entire site with the addition of native shrub and groundcover layers.

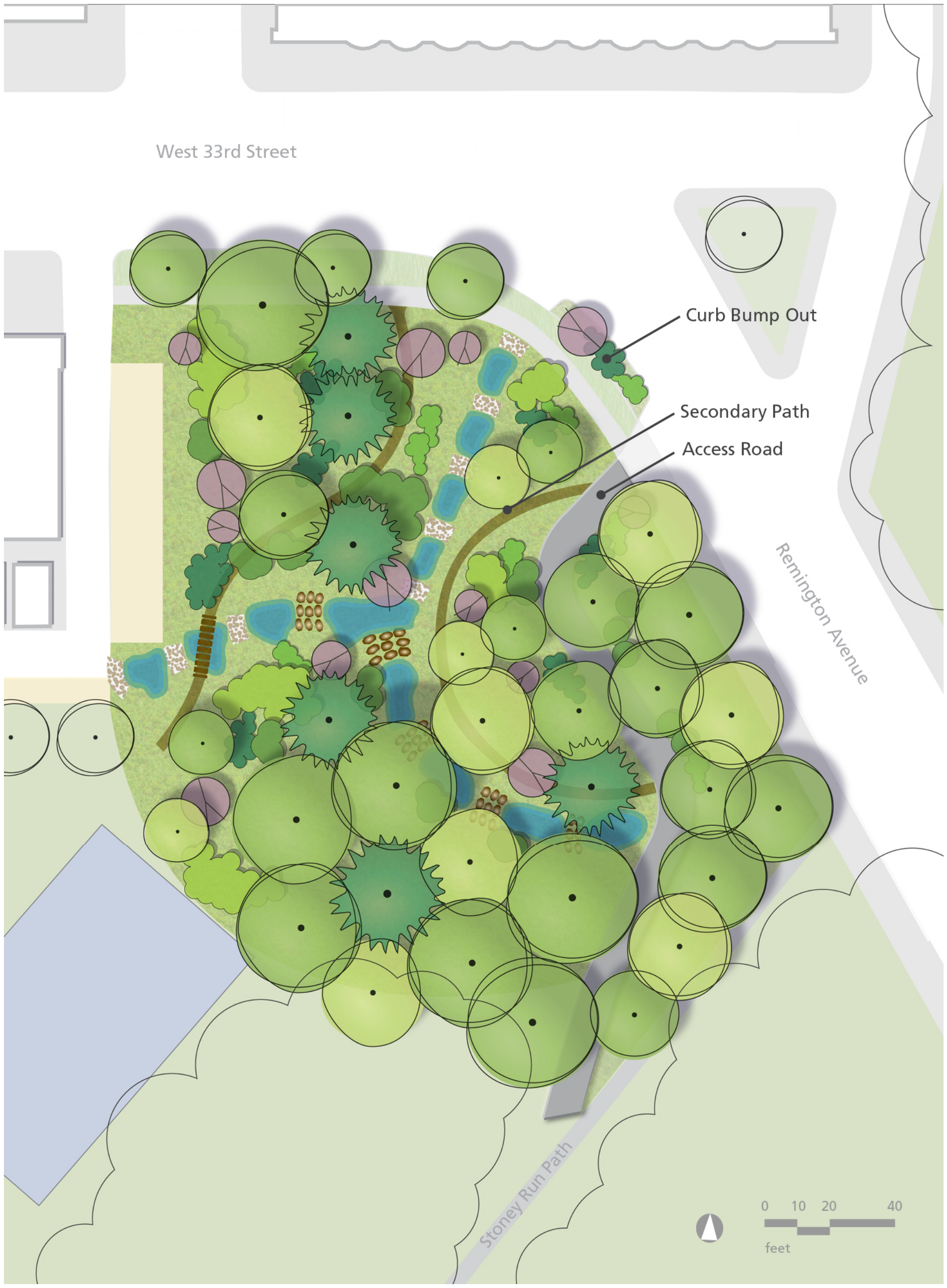


Figure 30. Illustrative plan enlargement

Two section views further communicate how the proposed design fits into the landscape. Section A–A' (Figure 31) looks to the northwest toward the houses across West 33rd Street. The section cuts through the first reach of the RSC coming from the houses showing the cobble weirs, pools and a boulder cascade leading to the central pool. The proposed curb bump out can be seen along the roadway with the second reach of the RSC leading from the road nestled into the landscape. Section B–B' (Figure 32) looks to the northeast toward the Stoney Run stream valley, cutting through the lower reach of the RSC. The longer boulder cascades between each pool can be seen, as well as a more complete view of the access road leading down into the Stoney Run stream valley.

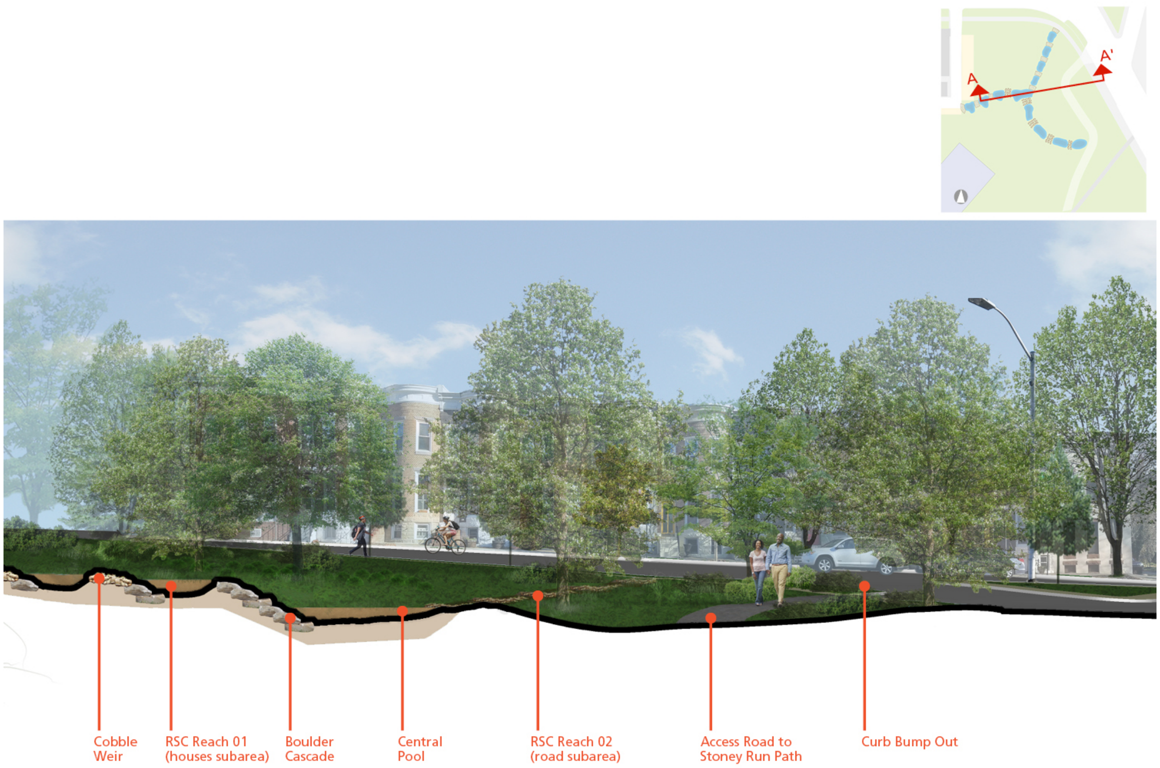


Figure 31. Section A–A'

Figure 32. Section B–B'

Finally, a perspective view (Figure 33) from within the park looks down the access road to the Stoney Run stream valley. The lower reach of the RSC with boulder cascades is in the background.

Figure 33. Perspective view

CHAPTER 7 Landscape Performance

According to the Landscape Architecture Foundation, landscape performance is "a measure of the effectiveness with which landscape solutions fulfill their intended purpose and contribute to sustainability." When landscapes are designed with the aim of heightening performance, assessment methods are needed to determine the success in meeting these goals (Sarah T. Lovell and Johnston 2009). The landscape performance paradigm seeks to improve the quality of designed landscapes by adopting performance measures to assess environmental, social and economic impact. (Yang, Li, and Binder 2016). A number of the goals of the case demonstration, tied to specific landscape performance measures, are examined below.

Water Quantity Performance

Goal: Convey the 100-year storm peak volume

To establish the water quantity performance of the proposed RSC, the conveyance capability of each of the three reaches of the proposed RSC must be determined. First, the hydrology of the proposed catchment with three subareas was modeled using the NRCS WIN TR-55 software to determine the peak flow volume of each subarea for the 100-year storm. The results, shown in Figure 34, were 7.94 cfs (0.22 cms) for the houses subarea, 7.46 cfs (0.21 cms) for the road subarea and 13.17 cfs (0.37 cms) for the outlet from the joint subarea.

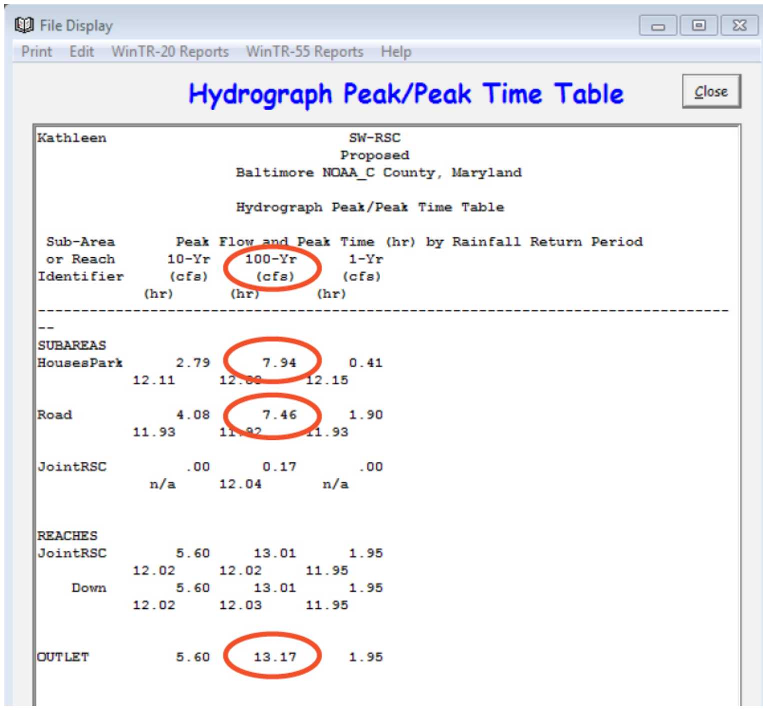


Figure 34. TR-55 peak flow for the proposed drainage subareas

Next, the maximum flow capacity of each reach of the proposed RSC was calculated using Manning's equation for open channel flow. The channel for all reaches of the proposed RSC is 8 feet (2.4 m) wide and 0.8 feet (0.24 m) deep; the average slope for the first (houses) and second (road) reaches of the RSC is 5 percent and the average slope for the third (joint) reach of the RSC is 15 percent.

$$Q = (1.49/n)\ (A)\ (R_h)^{2/3}\ (S)^{1/2}$$

Where: Q = 100 year ultimate flow (cfs)
1.49 = conversion factor
n = Manning’s n (0.05 for RSC)
A = cross-sec. area of riffle channel
R_h = hydraulic radius (ft)
S = average slope

RSC01 (houses) $Q = (1.49/0.05)\ (4.27)\ (0.52)\ (0.22) = 14.56$ cfs

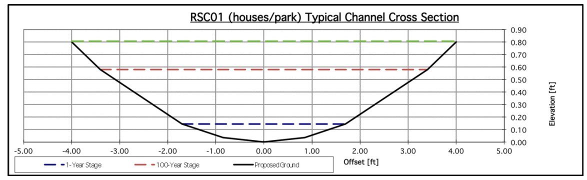
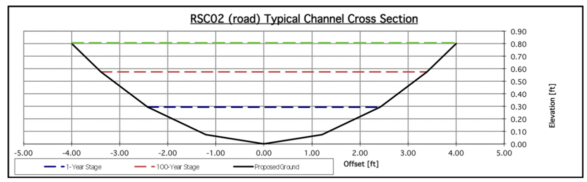
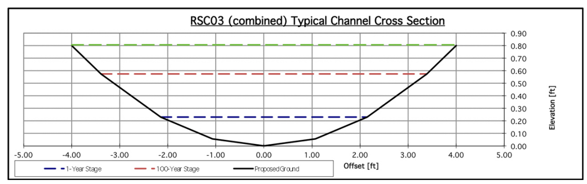
RSC02 (road) $Q = (1.49/0.05)\ (4.27)\ (0.52)\ (0.22) = 14.56$ cfs

RSC03 (joint) $Q = (1.49/0.05)\ (4.27)\ (0.52)\ (0.387) = 25.6$ cfs

Figure 35. Maximum flow capacity calculations

Finally, the two sets of figures were compared. The typical channel cross sections in the far right column of Table 2 represent the 8 foot (2.4 m) wide by 0.8 foot (0.24 m) deep channel in each of the three reaches of the proposed RSC. The water levels in the channel are indicated by the color-coded horizontal lines, with red corresponding to the 100-year peak flow as derived from TR-55 and green to the calculated max capacity. The blue line, shown for reference, indicates the water level during the 1-year storm peak flow. As can be seen by the position of the red line in each cross section, the proposed RSC design successfully accommodates the 100-year storm peak flow rate with additional capacity for even larger storm events.

Table 2. Water Quantity Performance Comparison

	TR-55 100-year Q	Calculated Max Capacity	Typical Channel Cross Section
RSC01 (houses)	7.94 cfs (0.22 cms)	14.56 cfs (0.41 cms)	
RSC02 (road)	7.46 cfs (0.21 cms)	14.56 cfs (0.41 cms)	
RSC03 (joint)	13.17 cfs (0.37 cms)	25.6 cfs (0.75 cms)	

Result: the proposed design exceeds the 100-year storm volume conveyance goal

Water Quality Performance

Goal: Capture and treat 1.0 inch (0.25 cm) of rainfall

To determine the quantity of rainfall that the proposed RSC is able to capture and treat, the storage volume of both the pools and the void spaces was calculated in acre feet (Figure 36). The result was then inserted into a standard stormwater retrofit equation (WQGIT 2014) to determine the inches of rainfall being treated by the system (Figure 37).

Storage Volume in Voids

$(D_f)\ (L)\ (W_f)\ (P)$

(2) (305) (4) (0.33) = 805 ft^3

Where: D_f = Depth of filter bed
L = Length of project
W_f = Width of filter bed
P = Porosity of 30%

Storage Volume in Pools

$(D_{out})\ (A)\ (0.85)$

(2) (2094) (0.85) = 3560 ft3

Where: D_{out} = Depth of pools
A = Surface area of pools
0.85 = Conversion factor

Total storage volume = 4365 ft^3 = 1.0 Acre Feet

Figure 36. Calculation of storage volume of proposed RSC system

$$\frac{(RS)\ (12)}{(I)\ (A)} = x \text{ inches}$$

Where: RS = Retrofit storage in acre-feet
12 = Conversion from ft to in
I = % impervious, as decimal
A = Drainage area in acres

$$\frac{(1.0 \text{ acre-feet})(12 \text{ in/ft})}{(0.44 \text{ impervious})(2.76 \text{ acres})} = \frac{1.2}{1.21} = 1.0 \text{ inch}$$

Figure 37. Standard retrofit equation

RSC is classified as a runoff reduction (RR) practice (WQGIT 2014; MD DOE 2014), therefore the RR retrofit removal curves (WQGIT 2012) are used to determine pollutant removal rates. For 1.0 inch (0.54 cm) of rainfall, 57 percent of total nitrogen is removed, 66 percent of total phosphorous is removed and 70 percent of total suspended solids are removed.

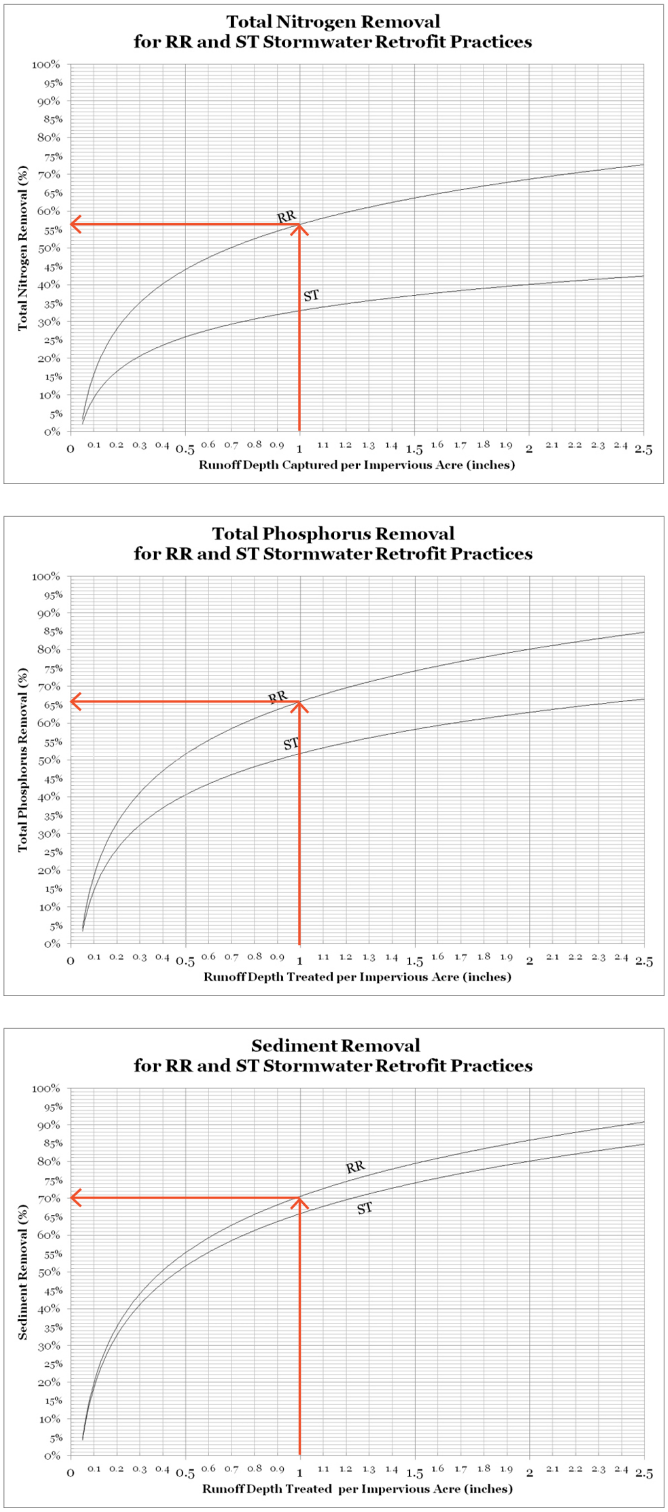


Figure 38. Pollutant removal curves

Using the Maryland Department of the Environment statewide weighted average urban pollutant loading rates (MD DOE 2014), the annual pollutant removal volumes for the proposed RSC system are shown in Table 3.

Table 3. Annual Pollutant Removal Volumes for the Proposed RSC

Total Nitrogen	Total Phosphorus	Total Suspended Solids
18.4 lbs (8.3 kg)	1.2 lbs (0.5 kg)	0.4 tons (363 kg)

Result: the proposed design meets the water quality goal to capture and treat 1.0 inch (0.54 cm) of rainfall.

Economic Performance of RSC

Goal: Quantify RSC Value

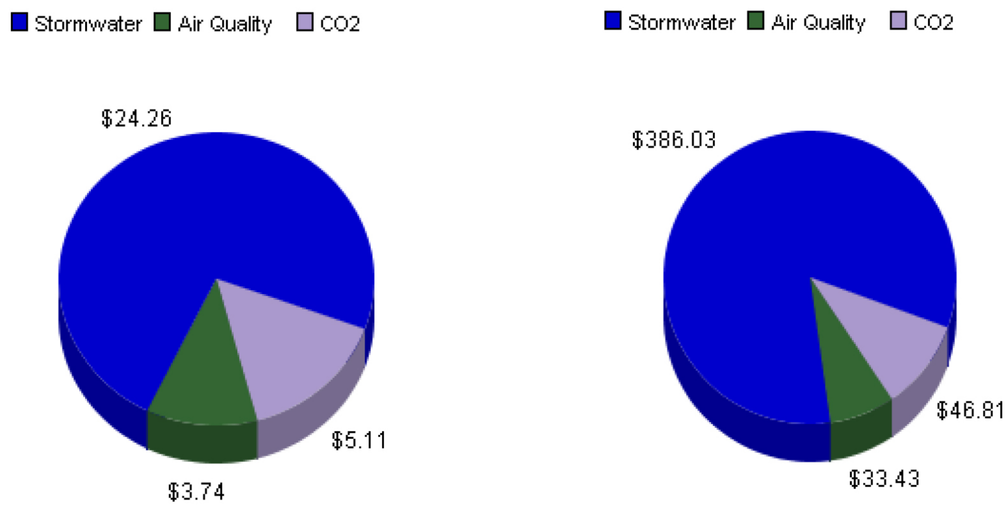
As part of her doctoral dissertation research, Adrienne Cizek performed an ecosystem service indicator analysis on nine RSC systems in Maryland and North Carolina in May of 2012 and 2014 (Cizek 2014). Examined ecosystem service indicators included climate regulation, soil formation, biodiversity, habitat provision and sociocultural services. Cizek determined the total mean value of the examined services provided by RSC systems for the first 15 years after installation to be US$ 20,500 per hectare, with a maximum value of $67,300 per hectare (Cizek 2014). Fifteen years is used as the benchmark, because that is the age of the oldest established RSC systems. Applying

Cizek's figures to the proposed case demonstration site of 2.76 acres, or 1.1 hectares, the estimated total value of the ecosystem services for the proposed RSC for the first 15 years after installation is between US$ 22,500 and US$ 75,030.

Economic Performance of Expanded Tree Canopy

Goal: Quantify Value of Increased Tree Canopy using USFS iTree Software

iTree is the USDA Forest Service's suite of peer-reviewed web-based software tool to asses urban forestry benefits. To estimate the value of the expanded tree canopy of the case demonstration design proposal, the web-based iTree Design application was used. To maintain consistency, the same 15 year benchmark that was used for the RSC ecosystem services valuation was also used for the iTree valuation. The total estimated benefit for the first 15 years of expanded tree canopy establishment is US$ 2,870. US$ 2,264 is the result of stormwater runoff savings by intercepting an estimated 228,686 gallons of rainfall; US$ 240 is air quality improvement savings by absorbing pollutants and lowering air temperature; and US$ 366 is from savings by reducing 37,698 lbs (17,100 kg) of atmospheric carbon dioxide. The charts in Figure 39 show the comparison of tree benefits in the first year and the fifteenth year.



Annual tree benefits for 2016 *Annual tree benefits for the year 2031*

Figure 39. Annual tree benefits for the first and fifteenth year after installation (iTree)

CHAPTER 8 Conclusion

The case demonstration in this thesis proposes to retrofit a poorly functioning impervious drainage in a small catchment in central Baltimore City with a Regenerative Stormwater Conveyance capable of capturing and treating 1.0 inch (2.45 cm) of stormwater runoff and conveying peak volumes in excess of the 100 year storm. The design proposal represents an novel application of RSC in both the high-density Baltimore City setting and the atypically small, 2.76 acre (1.1 ha) catchment size. By comparison, the precedent RSC systems discussed in Chapter 4 treat drainage areas ranging from 10 to 144 acres (4 to 58 ha), and the Maryland RSC systems examined by Cizek (2014) treat drainage areas ranging from 11 to 227 acres (4.4 to 92 ha). Restoring small urban drainages, however, is important for regaining the critical ecosystem services of headwater streams. Elmore and Kaushaul (2008) have determined that, in Baltimore City, 73 percent of headwater streams with drainages as small as 2.5 acres (1.0 ha) have been buried or directed into impervious culverts and channels. Therefore, while the design proposal in this thesis is specific to the project site, it has the potential to serve as a model for a City-wide approach to retrofitting small-scale impervious drainage systems and restoring headwater ecosystems.

Next Steps

The next step for the case demonstration proposal is to pursue implementation. After receiving positive feedback from professionals about the viability of the project, the designer is partnering with an ecological engineer experienced in green infrastructure projects in Baltimore City to present the design proposal to the Parks and People Foundation. The Parks and People Foundation is an established non-profit organization in Baltimore City with a track record of implementing green infrastructure projects on city-owned public land, as well as a green job training program for City youth ages 14 to 21.

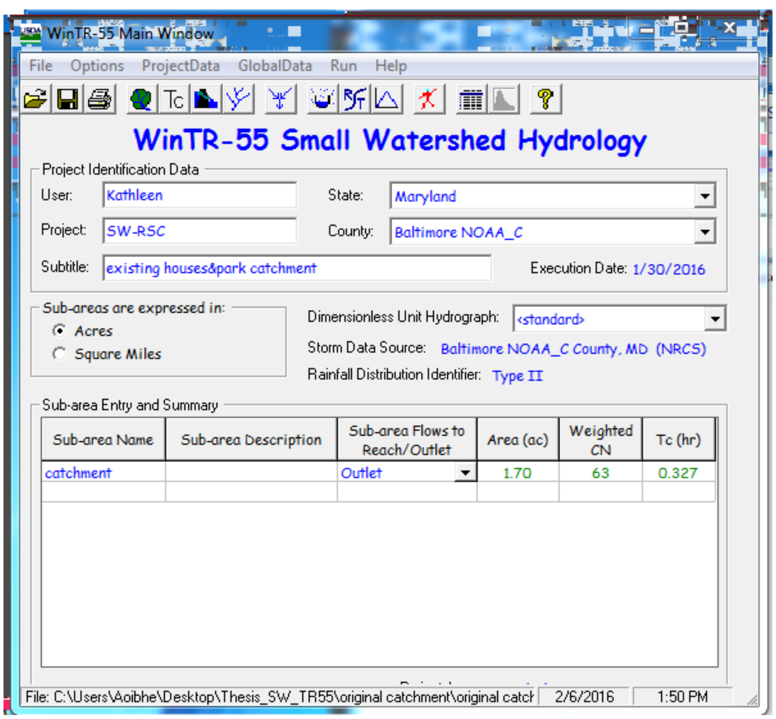
On a broader scale, the next step is to perform a suitability analysis to identify additional candidate sites for RSC retrofits in Baltimore City. Ecological, sociocultural and economic criteria must all be considered in order to maximize the potential value of the projects. Such an analysis will allow for the quantification of the potential impact of adopting the case demonstration model as a strategic tool in addressing Baltimore City's stormwater challenges.

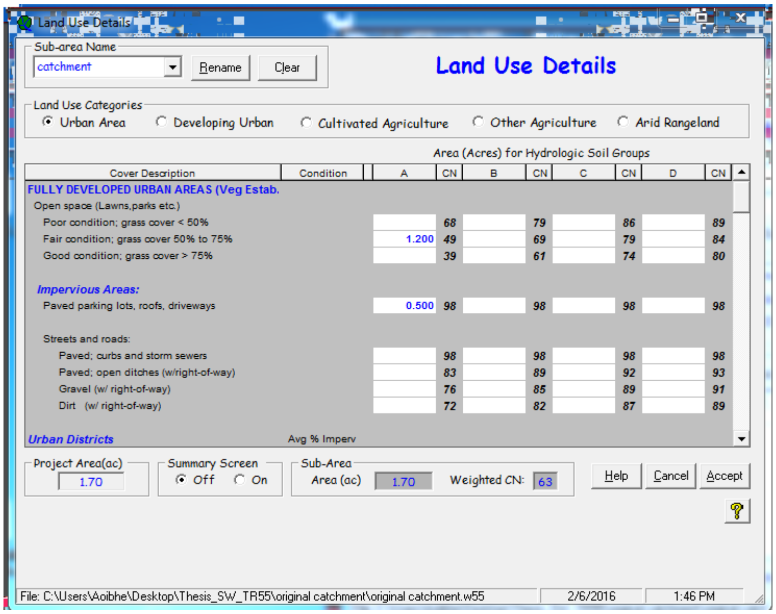
Appendix: Hydrologic Modeling with TR-55

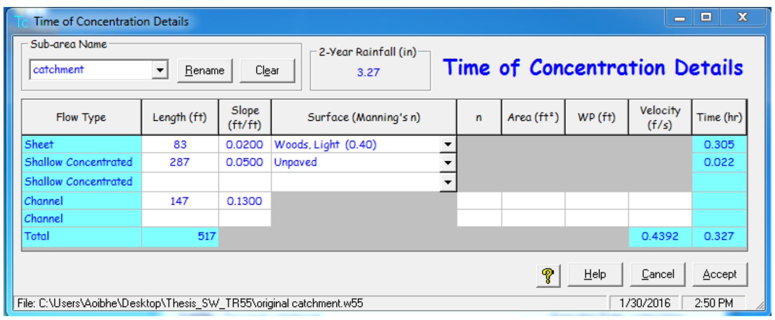
The following shows the complete modeling of the existing site hydrology and the design proposal hydrology using the USDA Natural Resources Conservation Service WinTR-55 Watershed Hydrology software.

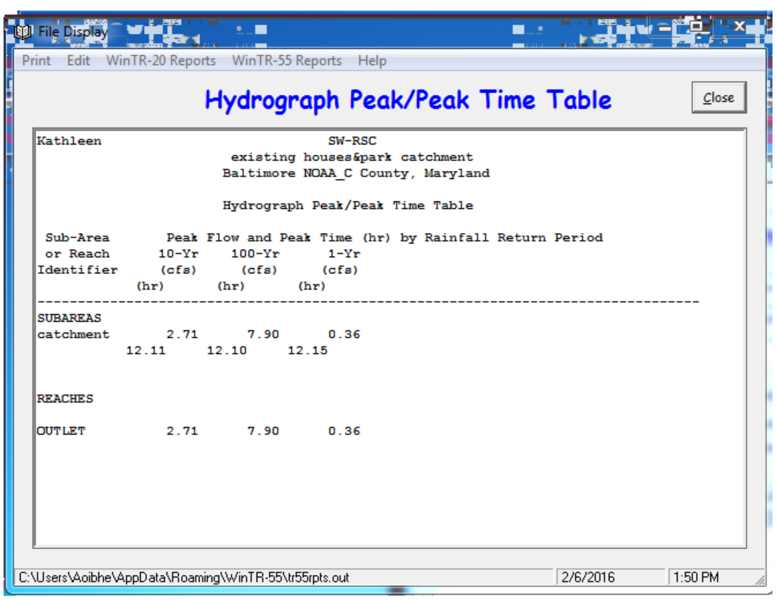
Existing Site Hydrology

Catchment 01 (houses and open space)

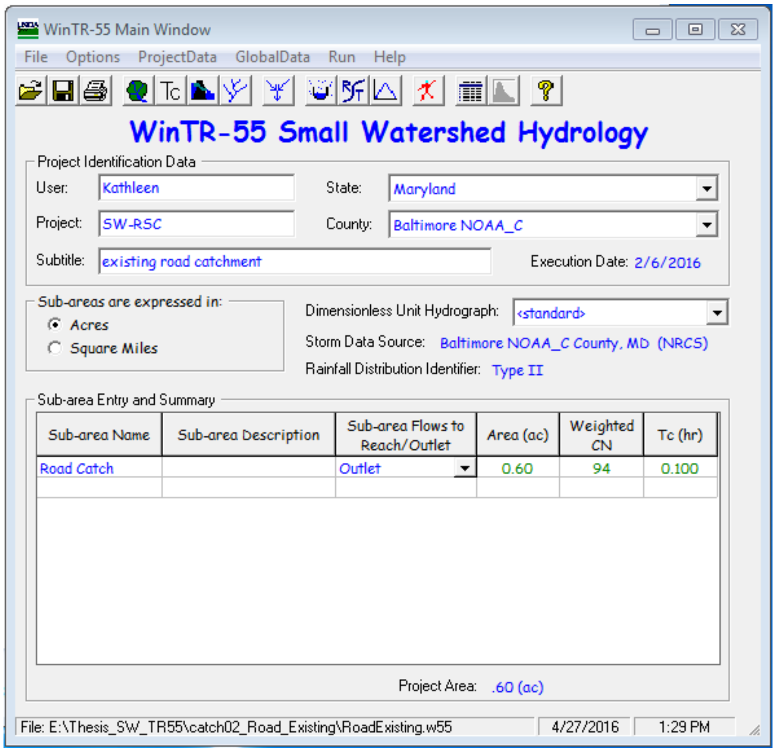


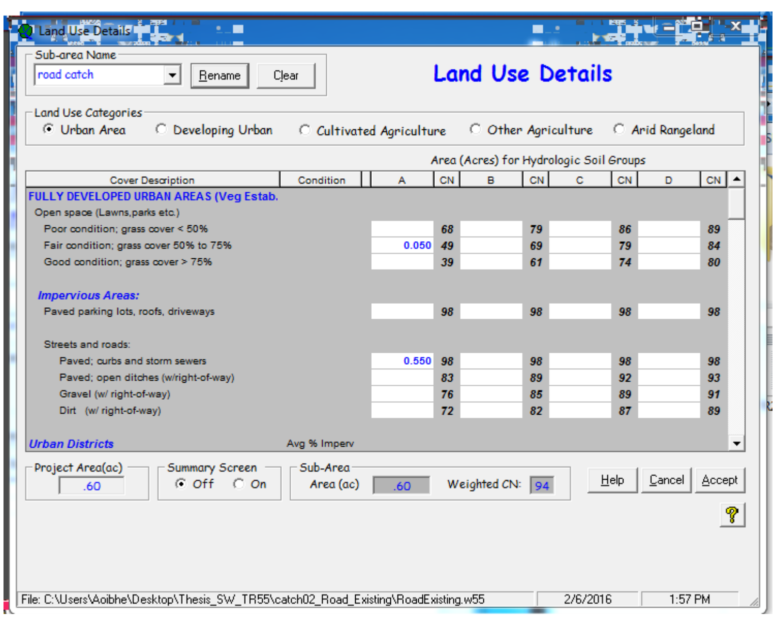

Land Use Details
Sub-area Name
catchment
Rename
Clear
Land Use Details
Land Use Categories
Urban Area
Developing Urban
Cultivated Agriculture
Other Agriculture
Arid Rangeland
Area (Acres) for Hydrologic Soil Groups
Cover Description
Condition
A
CN
B
CN
C
CN
D
CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.
Open space (Lawns,parks etc.)
Poor condition; grass cover < 50%
68 79 86 89
Fair condition; grass cover 50% to 75%
1.200 49 69 79 84
Good condition; grass cover > 75%
39 61 74 80
Impervious Areas:
Paved parking lots, roofs, driveways
0.500 98 98 98 98
Streets and roads:
Paved; curbs and storm sewers
98 98 98 98
Paved; open ditches (w/right-of-way)
83 89 92 93
Gravel (w/ right-of-way)
76 85 89 91
Dirt (w/ right-of-way)
72 82 87 89
Urban Districts
Avg % Imperv
Project Area(ac)
1.70
Summary Screen
Off
On
Sub-Area
Area (ac)
1.70
Weighted CN:
63
Help
Cancel
Accept
File: C:\Users\Aoibhe\Desktop\Thesis_SW_TR55\original catchment\original catchment.w55
2/6/2016
1:46 PM

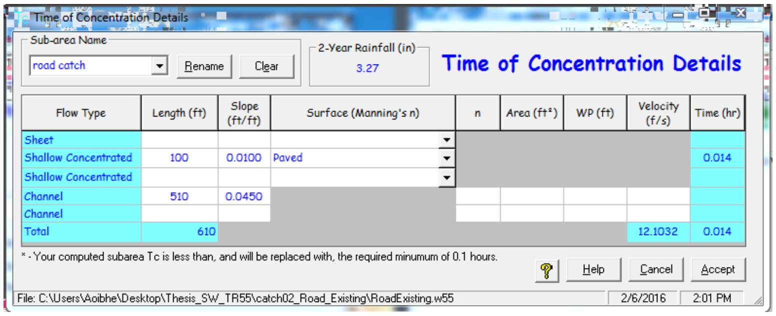

Time of Concentration Details
Sub-area Name
catchment
Rename
Clear
2-Year Rainfall (in)
3.27
Time of Concentration Details
Flow Type
Length (ft)
Slope (ft/ft)
Surface (Manning's n)
n
Area (ft²)
WP (ft)
Velocity (f/s)
Time (hr)
Sheet 83 0.0200 Woods, Light (0.40) 0.305
Shallow Concentrated 287 0.0500 Unpaved 0.022
Shallow Concentrated
Channel 147 0.1300
Channel
Total 517 0.4392 0.327
Help
Cancel
Accept
File: C:\Users\Aoibhe\Desktop\Thesis_SW_TR55\original catchment.w55
1/30/2016
2:50 PM


File Display
Print
Edit
WinTR-20 Reports
WinTR-55 Reports
Help
Hydrograph Peak/Peak Time Table
Close
Kathleen SW-RSC
existing houses&park catchment
Baltimore NOAA_C County, Maryland
Hydrograph Peak/Peak Time Table
Sub-Area Peak Flow and Peak Time (hr) by Rainfall Return Period
or Reach 10-Yr 100-Yr 1-Yr
Identifier (cfs) (cfs) (cfs)
(hr) (hr) (hr)
SUBAREAS
catchment 2.71 7.90 0.36
12.11 12.10 12.15
REACHES
OUTLET 2.71 7.90 0.36
C:\Users\Aoibhe\AppData\Roaming\WinTR-55\tr55rpts.out
2/6/2016
1:50 PM

Catchment 02 (road right of way)







Time of Concentration Details

Sub-area Name: road catch

2-Year Rainfall (in): 3.27

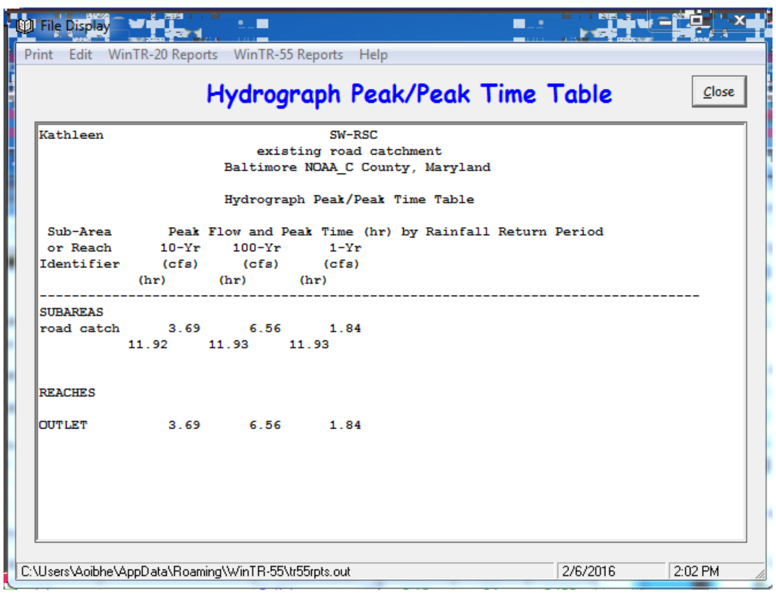
Time of Concentration Details

Flow Type	Length (ft)	Slope (ft/ft)	Surface (Manning's n)	n	Area (ft²)	WP (ft)	Velocity (f/s)	Time (hr)
Sheet								
Shallow Concentrated	100	0.0100	Paved					0.014
Shallow Concentrated								
Channel	510	0.0450						
Channel								
Total	610						12.1032	0.014

* - Your computed subarea Tc is less than, and will be replaced with, the required minumum of 0.1 hours.

Help Cancel Accept

File: C:\Users\Aoibhe\Desktop\Thesis_SW_TR55\catch02_Road_Existing\RoadExisting.w55 2/6/2016 2:01 PM



File Display

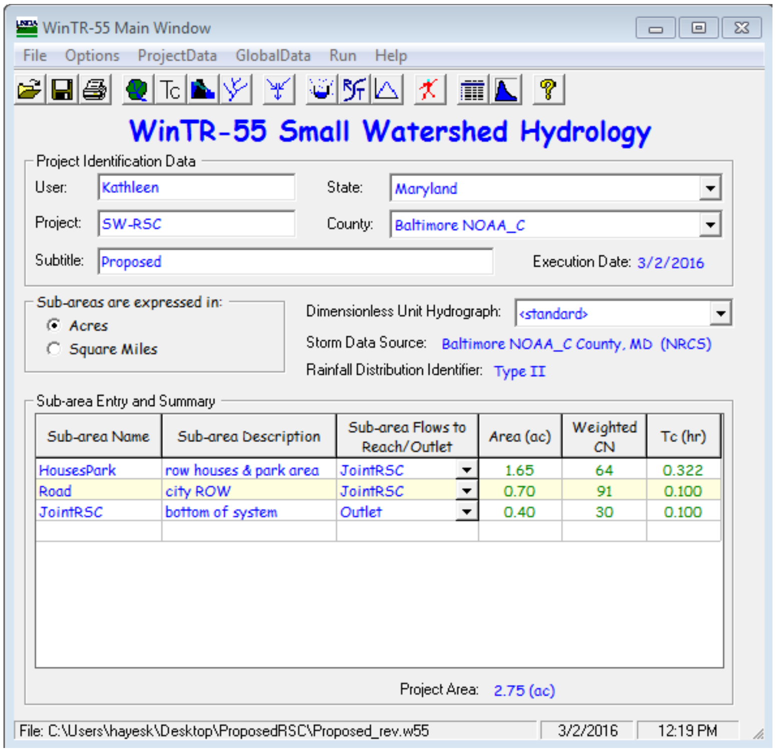
Print Edit WinTR-20 Reports WinTR-55 Reports Help

Hydrograph Peak/Peak Time Table

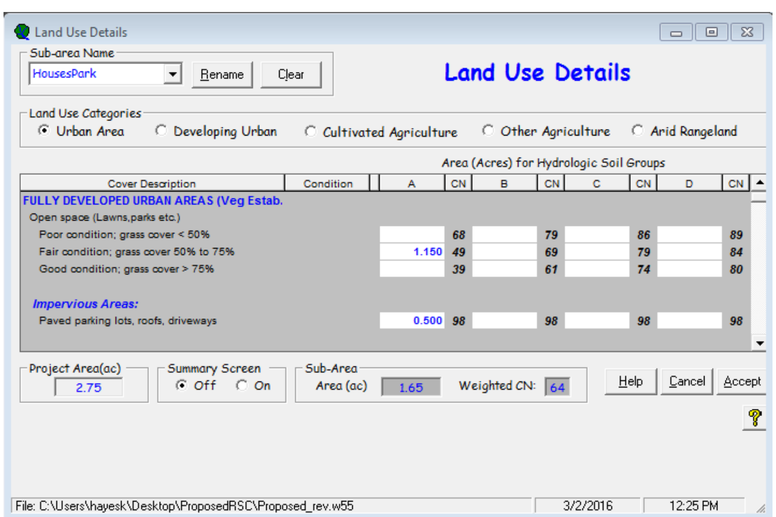
```
Kathleen                              SW-RSC
                           existing road catchment
                       Baltimore NOAA_C County, Maryland

                       Hydrograph Peak/Peak Time Table

 Sub-Area        Peak Flow and Peak Time (hr) by Rainfall Return Period
 or Reach       10-Yr     100-Yr       1-Yr
Identifier      (cfs)      (cfs)      (cfs)
            (hr)       (hr)       (hr)
----------------------------------------------------------------------------------
SUBAREAS
road catch       3.69       6.56       1.84
           11.92      11.93      11.93


REACHES

OUTLET           3.69       6.56       1.84
```

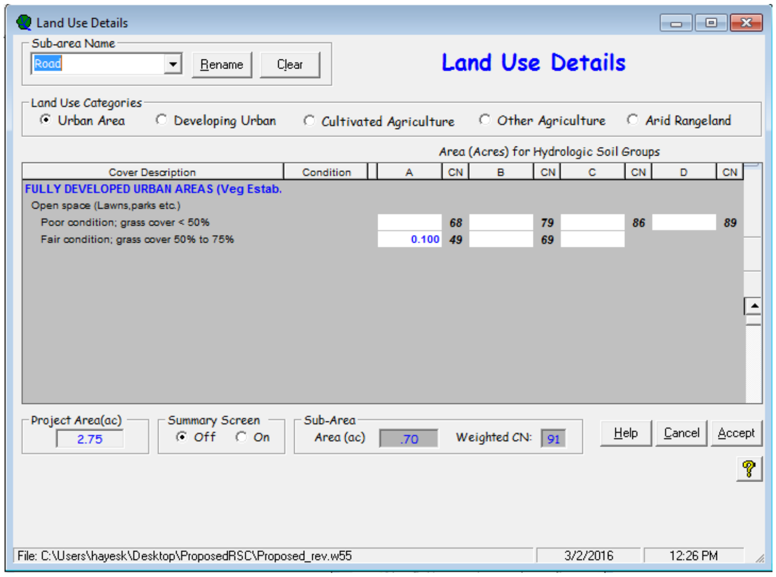
C:\Users\Aoibhe\AppData\Roaming\WinTR-55\tr55rpts.out 2/6/2016 2:02 PM

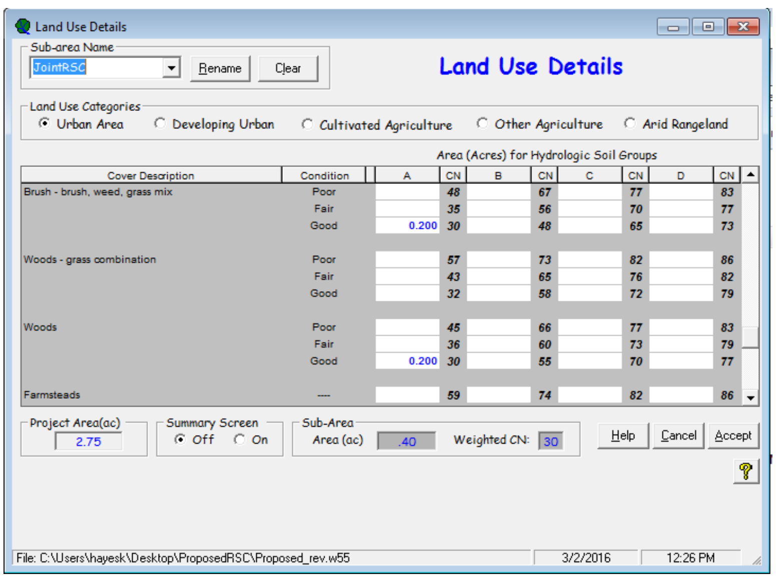
Design Proposal Hydrology



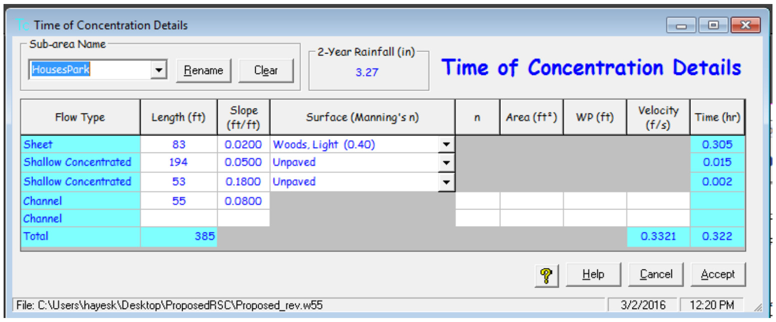
Land use details for each subarea




Land Use Details
Sub-area Name
Road
Rename
Clear
Land Use Details
Land Use Categories
Urban Area
Developing Urban
Cultivated Agriculture
Other Agriculture
Arid Rangeland
Area (Acres) for Hydrologic Soil Groups
Cover Description
Condition
A
CN
B
CN
C
CN
D
CN
FULLY DEVELOPED URBAN AREAS (Veg Estab.
Open space (Lawns,parks etc.)
Poor condition; grass cover < 50%
68
79
86
89
Fair condition; grass cover 50% to 75%
0.100
49
69
Project Area(ac)
2.75
Summary Screen
Off
On
Sub-Area
Area (ac)
.70
Weighted CN:
91
Help
Cancel
Accept
File: C:\Users\hayesk\Desktop\ProposedRSC\Proposed_rev.w55
3/2/2016
12:26 PM


Land Use Details
Sub-area Name
JointRSC
Rename
Clear
Land Use Details
Land Use Categories
Urban Area
Developing Urban
Cultivated Agriculture
Other Agriculture
Arid Rangeland
Area (Acres) for Hydrologic Soil Groups
Cover Description
Condition
A
CN
B
CN
C
CN
D
CN
Brush - brush, weed, grass mix
Poor
48
67
77
83
Fair
35
56
70
77
Good
0.200
30
48
65
73
Woods - grass combination
Poor
57
73
82
86
Fair
43
65
76
82
Good
32
58
72
79
Woods
Poor
45
66
77
83
Fair
36
60
73
79
Good
0.200
30
55
70
77
Farmsteads
59
74
82
86
Project Area(ac)
2.75
Summary Screen
Off
On
Sub-Area
Area (ac)
.40
Weighted CN:
30
Help
Cancel
Accept
File: C:\Users\hayesk\Desktop\ProposedRSC\Proposed_rev.w55
3/2/2016
12:26 PM

Time of concentration details for each subarea



Time of Concentration Details

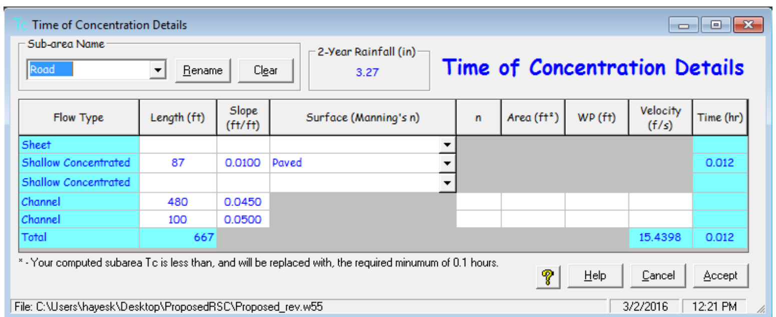
Sub-area Name: HousesPark | Rename | Clear | 2-Year Rainfall (in): 3.27

Time of Concentration Details

Flow Type	Length (ft)	Slope (ft/ft)	Surface (Manning's n)	n	Area (ft²)	WP (ft)	Velocity (f/s)	Time (hr)
Sheet	83	0.0200	Woods, Light (0.40)					0.305
Shallow Concentrated	194	0.0500	Unpaved					0.015
Shallow Concentrated	53	0.1800	Unpaved					0.002
Channel	55	0.0800						
Channel								
Total	385						0.3321	0.322

Help | Cancel | Accept

File: C:\Users\hayesk\Desktop\ProposedRSC\Proposed_rev.w55 | 3/2/2016 | 12:20 PM



Time of Concentration Details

Sub-area Name: Road | Rename | Clear | 2-Year Rainfall (in): 3.27

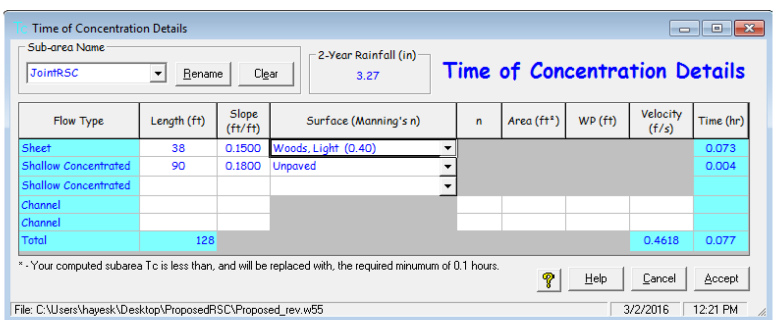
Time of Concentration Details

Flow Type	Length (ft)	Slope (ft/ft)	Surface (Manning's n)	n	Area (ft²)	WP (ft)	Velocity (f/s)	Time (hr)
Sheet								
Shallow Concentrated	87	0.0100	Paved					0.012
Shallow Concentrated								
Channel	480	0.0450						
Channel	100	0.0500						
Total	667						15.4398	0.012

* - Your computed subarea Tc is less than, and will be replaced with, the required minumum of 0.1 hours.

Help | Cancel | Accept

File: C:\Users\hayesk\Desktop\ProposedRSC\Proposed_rev.w55 | 3/2/2016 | 12:21 PM



Time of Concentration Details

Sub-area Name: JointRSC | Rename | Clear | 2-Year Rainfall (in): 3.27

Time of Concentration Details

Flow Type	Length (ft)	Slope (ft/ft)	Surface (Manning's n)	n	Area (ft²)	WP (ft)	Velocity (f/s)	Time (hr)
Sheet	38	0.1500	Woods, Light (0.40)					0.073
Shallow Concentrated	90	0.1800	Unpaved					0.004
Shallow Concentrated								
Channel								
Channel								
Total	128						0.4618	0.077

* - Your computed subarea Tc is less than, and will be replaced with, the required minumum of 0.1 hours.

Help | Cancel | Accept

File: C:\Users\hayesk\Desktop\ProposedRSC\Proposed_rev.w55 | 3/2/2016 | 12:21 PM

Hydrograph Peak/Peak Time Table

File Display

Print Edit WinTR-20 Reports WinTR-55 Reports Help

Hydrograph Peak/Peak Time Table

Close

```
Kathleen                                   SW-RSC
                                          Proposed
                        Baltimore NOAA_C County, Maryland

                        Hydrograph Peak/Peak Time Table

 Sub-Area        Peak Flow and Peak Time (hr) by Rainfall Return Period
 or Reach       10-Yr     100-Yr       1-Yr
Identifier      (cfs)      (cfs)      (cfs)
            (hr)       (hr)       (hr)
--------------------------------------------------------------------------------
--
SUBAREAS
HousesPark       2.79       7.94       0.41
           12.11      12.08      12.15

Road             4.08       7.46       1.90
           11.93      11.92      11.93

JointRSC          .00       0.17        .00
             n/a      12.04        n/a


REACHES
JointRSC         5.60      13.01       1.95
           12.02      12.02      11.95
    Down         5.60      13.01       1.95
           12.02      12.03      11.95


OUTLET           5.60      13.17       1.95
```

C:\Users\hayesk\AppData\Roaming\WinTR-55\tr55rpts.out | 3/2/2016 | 12:1

References

Baltimore Commission on Sustainability. 2009. “Baltimore Sustainability Plan.” City of Baltimore.

Baltimore Ecosystem Study. 2013. “Sanitary City.” *BES Urban Lexicon*. March 23. http://besurbanlexicon.blogspot.com/2013/03/sanitary-city.html.

Batten, Leslie, and Nancy D. Rottle. 2011. “Reclaiming Urban Waterfronts through Green Stormwater Solutions.” *The International Journal of Environmental, Cultural, Economic and Social Sustainability* 7 (6): 251–70.

Beck, Travis. 2013. *Principles of Ecological Landscape Design*. Washington, DC: Island Press.

Beisner, BE, DT Haydon, and K Cuddington. 2003. “Alternative Stable States in Ecology.” *Frontiers in Ecology and the Environment* 1 (7): 376–82.

Benedict, Mark A., and Edward T. McMahon. 2006. *Green Infrastructure: Linking Landscapes and Communities*. Washington, DC: Island Press.

Benyus, Janine M. 2002. *Biomimicry : Innovation Inspired by Nature*. New York : Perennial,.

Berg, Joe. 2009. “Baseflow Stream Channel Design: An Approach to Restoration That Optimizes Resource Values And Ecosystem Services.” *Water Resources IMPACT* 11 (5): 14–16.

Berg, Joe, and Keith Underwood. 2012. “Regenerative Stormwater Conveyance Provides Needed Treatment for Runoff Volume, Peak Discharge, and Quality Control for New Development or Retrofitting Underserved Watersheds.” *Proceedings of the Water Environment Federation* 2012 (5): 696–99.

Blue Water Baltimore. 2015. “Healthy Harbor 2014 Report Card.”

BNIA-JFI. 2015. “Vital Signs 13 [Data File].” Retrieved from http://www.bniajfi.org/vital_signs.

Boone, Christopher G. 2003. “Obstacles to Infrastructure Provision: The Struggle to Build Comprehensive Sewer Works in Baltimore.” *Historical Geography* 31: 151–68.

Bridgewater, Peter, Eric S. Higgs, Richard J. Hobbs, and Stephen T. Jackson. 2011. “Engaging with Novel Ecosystems.” *Frontiers in Ecology and the Environment* 9 (8): 423–423.

Browning, Maura. 2010. “A Seepage Wetland Design Approach to Stream Restoration: A Better Model for Urban Storm Water Management in Wilelinor Stream Watershed.” In *A Sustainable Chesapeake*, 43–52. Arlingon, Virginia: The Conservation Fund.

Brown, Ted, Joe Berg, and Keith Underwood. 2010. “Regenerative Stormwater Conveyance: An Innovative Approach to Meet a Range of Stormwater

Management and Ecological Goals." *World Environ. Water Resour. Congress 2010: Challenges of Change*.

Brown, Ted, Dowdell, J., Richter, S., and Porter, L. 2015. "Integrated LID and Green Infrastructure Planning at Rutgers University to Achieve Better Ecological Outcomes at Lower Cost." *Low Impact Develoment Technology*, 106.

Butler, David R., and George P. Malanson. 2005. "The Geomorphic Influences of Beaver Dams and Failures of Beaver Dams." *Dams in Geomorphology33rd Annual Binghampton International Geomorphology Symposium* 71 (1–2): 48–60. doi:10.1016/j.geomorph.2004.08.016.

Cappiella, Karen, Lisa Fraley-McNeal, Mike Novotney, and Schueler, Tom. 2008. "The Next Generation of Stormwater Wetlands." Wetlands and Watersheds. Article 5: Center for Watershed Protection.

Chesapeake Bay Trust. 2015. "New Grant Program Announced to Foucs on Stream Restoration Process," June 10. http://www.cbtrust.org/site/c.miJPKXPCJnH/b.9233873/k.4BF1/Restoration_Research_Grant_Program.htm.

Chesapeake Stormwater Network. 2014. "Cabin Branch Restoration: Best Urban BMP Award (BUBBA) for Best Stream Restoration."

Chow, Rudolph S., Sean Searles, Lynette Cardoch, Jane McLamarrah, and Chris DeHanas. 2014. "Using Triple Bottom Line Benefits Scoring to Prioritize Infrastructure Spending in Baltimore." *Proceedings of the Water Environment Federation* 2014 (1): 1–11.

Cizek, Adrienne R. 2014. "Quantifying the Stormwater Mitigation Performance and Ecosystem Service Provision in Regenerative Stormwater Conveyance (RSC)." PhD dissertation, North Carolina State University.

Cizek, Adrienne R., and William F. Hunt. 2013. "Defining Predevelopment Hydrology to Mimic Predevelopment Water Quality in Stormwater Control Measures (SCMs)." *Ecological Engineering* 57 (August): 40–45. doi:10.1016/j.ecoleng.2013.04.016.

Collett, Brad, Valerie Friedmann, and Wyn Miller. 2013. "Low Impact Development: Opportunities for the PlanET Region."

Costanza, Robert, Ralph d' Arge, Rudolph de Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387 (May): 253–60.

Elmore, Andrew J, and Sujay S Kaushal. 2008. "Disappearing Headwaters: Patterns of Stream Burial due to Urbanization." *Frontiers in Ecology and the Environment* 6 (6): 308–12. doi:10.1890/070101.

Feldman, Bob. 2015. "Did That Move?" *Wyman Park Community Association Newsletter* 15 (1): 4.

Filoso, Solange, and Margaret Palmer. 2009. "Stream Restoration Can Improve Water Quality but Is far from Being the Silver Bullet Solution." *Water Resources IMPACT* 11 (5): 17–18.

———. 2011. "Assessing Stream Restoration Effectiveness at Reducing Nitrogen Export to Downstream Waters." *Ecological Applications* 21 (6): 1989–2006.

Flores, Hala E., Sally Hornor, Ryan M. O'Banion, and Karl Neidhardt. 2012. "Volunteer Post-Construction Monitoring of Stormwater Attenuation in a Regenerative Step Pool Storm Conveyance System Retrofit." *Proceedings of the Water Environment Federation* 2012 (5): 649–65. doi:10.2175/193864712811699573.

Flores, Hala, J Markusic, C Victoria, R Bowen, and G Ellis. 2009. "Implementing Regenerative Stormwater Conveyance Restoration Techniques in Anne Arundel County: An Innovative Approach to Stormwater Management." *Water Resources IMPACT* 11 (5): 5–7.

Flores, Hala, Dennis McMonigle, and Keith Underwood. 2012. "Regenerative Step Pool Conveyance Design Guidelines." Revision 5. Anne Arundel County Department of Public Works. http://www.aacounty.org/DPW/Watershed/StepPoolStormConveyance.cfm.

Gilbeau, Gaby. 2016. "Millions of Gallons of Sewage-Contaminated Water Overflowing in Baltimore." *Chesapeake Bay Foundation Blog*. April 12. http://cbf.typepad.com/chesapeake_bay_foundation/.

Harrison, Jason W., and Wesley M. Knapp. 2010. "Ecological Classification of Groundwater-Fed Seepage Wetlands of the Maryland Coastal Plain."

Hobbs, Richard J., Salvatore Arico, James Aronson, Jill S. Baron, Peter Bridgewater, Viki A. Cramer, Paul R. Epstein, et al. 2006. "Novel Ecosystems: Theoretical and Management Aspects of the New Ecological World Order." *Global Ecology and Biogeography* 15 (1): 1–7. doi:10.1111/j.1466-822X.2006.00212.x.

Hobbs, Richard J., Eric Higgs, and James A. Harris. 2009. "Novel Ecosystems: Implications for Conservation and Restoration." *Trends in Ecology & Evolution* 24 (11): 599–605. doi:10.1016/j.tree.2009.05.012.

Hunter, MaryCarol. 2011. "Using Ecological Theory to Guide Urban Planting Design An Adaptation Strategy for Climate Change." *Landscape Journal* 30 (2): 173–93.

Kaushal, Sujay S., Peter M. Groffman, Paul M. Mayer, Elise Striz, and Arthur J. Gold. 2008. "Effects of Stream Restoration on Denitrification in an Urbanizing Watershed." *Ecological Applications* 18 (3): 789–804. doi:10.2307/40062186.

Kenny, Jillian, Cheryl Desha, Arun Kumar, and Charlie Hargroves. 2012. "Using Biomimicry to Inform Urban Infrastructure Design That Addresses 21st Century Needs." In *1st International Conference on Urban Sustainability and Resilience: Conference Proceedings*. UCL London. http://eprints.qut.edu.au/70168/.

Koch, Benjamin J., Catherine M. Febria, Roger M. Cooke, Jacob D. Hosen, Matthew E. Baker, Abigail R. Colson, Solange Filoso, et al. 2015. "Suburban Watershed Nitrogen Retention: Estimating the Effectiveness of Stormwater Management Structures." *Elementa: Science of the Anthropocene* 3 (July): 000063. doi:10.12952/journal.elementa.000063.

Lovell, Sarah Taylor, and Douglas M Johnston. 2008. "Creating Multifunctional Landscapes: How Can the Field of Ecology Inform the Design of the Landscape?" *Frontiers in Ecology and the Environment* 7 (4): 212–20. doi:10.1890/070178.

Lovell, Sarah T., and Douglas M. Johnston. 2009. "Designing Landscapes for Performance Based on Emerging Principles in Landscape Ecology." *Ecology and Society* 14 (1): 44.

Lundholm, Jeremy T., and Paul J. Richardson. 2010. "MINI-REVIEW: Habitat Analogues for Reconciliation Ecology in Urban and Industrial Environments: Habitat Analogues." *Journal of Applied Ecology* 47 (5): 966–75. doi:10.1111/j.1365-2664.2010.01857.x.

Manhattan Beach Coastal Plain Outfall. 2011. CCLLCTV. https://www.youtube.com/watch?v=t2f9f7Cfk1c&feature=youtu.be.

MD DOE. 2009. "2000 Maryland Stormwater Manual Design Manual, Volumes I & II." Baltimore, MD: Maryland Department of the Environment—Water Management Administration. http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/MarylandStormwaterDesignManual/Pages/Programs/WaterPrograms/SedimentandStormwater/stormwater_design/index.aspx.

———. 2014. "Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated: Guidance for National Pollutant Discharge Elimination System Stormwater Permits." Baltimore, MD: Maryland Department of the Environment.

Meyer, Judy L., David L. Strayer, J. Bruce Wallace, Sue L. Eggert, Gene S. Helfman, and Norman E. Leonard. 2007. "The Contribution of Headwater Streams to Biodiversity in River Networks1: The Contribution of Headwater Streams to Biodiversity in River Networks." *JAWRA Journal of the American Water Resources Association* 43 (1): 86–103. doi:10.1111/j.1752-1688.2007.00008.x.

Miller, James R., and Richard J. Hobbs. 2002. "Conservation Where People Live and Work." *Conservation Biology* 16 (2): 330–37. doi:10.2307/3061359.

Mozingo, Louise A. 1997. "The Aesthetics of Ecological Design: Seeing Science as Culture." *Landscape Journal* 16 (1): 46.

Musacchio, Laura R. 2011. "The Grand Challenge to Operationalize Landscape Sustainability and the Design-in-Science Paradigm." *Landscape Ecology* 26 (1): 1–5. doi:10.1007/s10980-010-9562-2.

Mussman, Ellen. 2016. "Jones Falls Watershed - Baltimore County." Accessed April 9. http://www.baltimorecountymd.gov/Agencies/environment/watersheds/jonesmain.html.

Nassauer, Joan Iverson, and Paul Opdam. 2008. "Design in Science: Extending the Landscape Ecology Paradigm." *Landscape Ecology* 23 (6): 633–44. doi:10.1007/s10980-008-9226-7.

Novotny, Vladmir, Jack Ahern, and Paul Brown. 2010. "Planning and Design for Sustainable and Resilient Cities: Theories, Strategies, and Best Practices for Green Infrastructure." In *Water Centric Sustainable Communities: Planning, Retrofitting, and Building the Next Urban Environment*. 135-176: John Wiley & Sons.

"NRCS Web Soil Survey." 2016. Accessed April 10. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

O'Farrell, Patrick J, and Pippin ML Anderson. 2010. "Sustainable Multifunctional Landscapes: A Review to Implementation." *Current Opinion in Environmental Sustainability* 2 (1-2): 59–65. doi:10.1016/j.cosust.2010.02.005.

Palmer, Margaret, Emily Bernhardt, Elizabeth Chornesky, Scott Collins, and et al. 2004. "Ecology for a Crowded Planet." *Science* 304 (5675): 1251–52.

Palmer, Margaret, Solange Filoso, and Rosemary Fanelli. 2014. "From Ecosystems to Ecosystem Services: Stream Restoration as Ecological Engineering." *Ecological Engineering* 65 (April): 62–70. doi:10.1016/j.ecoleng.2013.07.059.

Palmer, Margaret, and David Richardson. 2009. "Provisioning Services: A Focus on Fresh Water." In *The Princeton Guide to Ecology*, edited by Simon Levin, 625–33. Princeton: Princeton University Press.

Pelletier, Jeffrey S., and Wazir Qadri. 2014. "One Size Storm Does Not Fit All: Development of a Wet Weather SSO Elimination Plan for the City of Baltimore Using Continuous Model Simulation." *Proceedings of the Water Environment Federation* 2014 (4): 1–14.

Pred, Alan. 1990. *Making Histories and Constructing Human Geographies: The Local Transformation of Practice, Power Relations, and Consciousness*. Boulder: Westview Press.

Ranier, Thomas, and Claudia West. 2015. *Planting in a Post-Wild World: Designing Plant Communities for Resilent Landscapes*. Portland: Timber Press.

Severn Riverkeeper. 2013. "Cabin Branch Stream Restoration."

Shuster, W. D., J. Bonta, H. Thurston, E. Warnemuende, and D. R. Smith. 2005. "Impacts of Impervious Surface on Watershed Hydrology: A Review." *Urban Water Journal* 2 (4): 263–75. doi:10.1080/15730620500386529.

"Stoney Run Station." 2016. *Harbor Alert, Baltimore Harbor Waterkeeper Water Quality Monitoring*. January 12. http://www.harboralert.org/stations/33.

Storey, R, B Parkyn, B Smith, G Croker, and P Franklin. 2009. "Effects of Development on Zero-Order Steams in the Waikato Region." Environment Waikato.

Termorshuizen, Jolande W., and Paul Opdam. 2009. "Landscape Services as a Bridge between Landscape Ecology and Sustainable Development." *Landscape Ecology* 24 (8): 1037–52. doi:10.1007/s10980-008-9314-8.

Underwood, Keith R., William B. Moulden, Dennis C. McMonigle, and David J. Wallace. 2005. "Atlantic White Cedar Species Recovery and Wetland Enhancement Project at Howard's Branch, Anne Arundel County, Maryland." *Atlantic White Cedar: Ecology, Restoration, and Management*, 54.

US EPA. 2000. "Low Impact Development (LID): A Literature Review." EPA-841-B-00-005. United States Environmental Protection Agency.

———. 2010. "Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment." United States Environmental Protection Agency.

"Walk Score Methodology." 2016. Accessed April 9. https://www.walkscore.com/methodology.shtml.

Wheeler, Timothy B. 2015. "City Faulted for Deliberately Dumping Sewage into Jones Falls." *Baltimore Sun*, December 15. http://www.baltimoresun.com/features/green/blog/bs-md-ci-sewer-overflows-20151214-story.html.

WQGIT. 2012. "Recommendations of the Expert Panel to Define Removal Rates for Urban Stormwater Retrofit Practices." Chesapeake Stormwater Network and EPA Chesapeake Bay Program.

———. 2014. "Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects." Annapolis, MD: Chesapeake Stormwater Network and EPA Chesapeake Bay Program.

Wright, Justin P., Clive G. Jones, and Alexander S. Flecker. 2002. "An Ecosystem Engineer, the Beaver, Increases Species Richness at the Landscape Scale." *Oecologia* 132 (1): 96–101. doi:10.1007/s00442-002-0929-1.

Yang, Bo, Shujuan Li, and Chris Binder. 2016. "A Research Frontier in Landscape Architecture: Landscape Performance and Assessment of Social Benefits." *Landscape Research* 41 (3): 314–29. doi:10.1080/01426397.2015.1077944.