

ABSTRACT

CIZEK, ADRIENNE ROSE. Quantifying the Stormwater Mitigation Performance and Ecosystem Service Provision in Regenerative Stormwater Conveyance (RSC). (Under the direction of William F. Hunt, III.)

As part of Low Impact Development (LID), stormwater control measures (SCMs) are expected to mimic pre-development hydrology. This generally results in a comparison between outflow volumes discharged from SCMs and a target condition annual runoff. Such a simplistic evaluation overlooks multiple pathways of water present in target watersheds and SCMs, namely shallow interflow and groundwater surge. Chapter 2 suggests a more refined means of evaluating cognate conditions for SCMs in terms of hydrology and effluent water quality by discretizing SCM discharge into three pathways: runoff, shallow interflow, and groundwater surge.

Regenerative stormwater conveyance (RSC) is a new LID approach to stormwater mitigation. Surface runoff entering an RSC exits the system as surface flow, seepage, exfiltration into parent soil, or evapotranspiration (ET). Chapter 3 presents the hydrologic analysis of an RSC located in the Coastal Plain, North Carolina. Chapter 4 presents the water quality and hydrologic analysis of an RSC in the Piedmont, North Carolina. Both RSCs effectively reduced surface flows by 80% to 95%, converting most to seepage. The Piedmont RSC reduced TSS, TP, and TN in surface flow by 72%, 28%, and 30%, respectively, likely due to physical treatment processes.

RSCs mitigate stormwater runoff by converting most surface flow to subsurface seepage. Chapter 5 uses in-situ ultraviolet-visual spectroscopy to measure nitrogen in seepage during simulated storm events at a field-scale RSC. PLSR models of good fit were produced for nitrate and total Kjeldahl nitrogen (TKN), but not for total ammonia nitrogen. Subsurface nitrate and TKN concentrations were reduced by

30% and 22%, respectively. Progressing reductions over time indicate that biological activity contributed to nitrogen reductions. Nitrogen is better removed through seepage than through surface flow, however, nitrogen loading in seepage can be larger than that of surface flow. Further research is needed to examine subsurface pollutant reductions under varying hydrologic and seasonal conditions.

Healthy aquatic ecosystems are essential for promoting and sustaining human life. However, human development has resulted in the conversion of land from natural ecosystems to urban and suburban areas. Per their nature-based design, RSCs have a high potential to offer additional ecosystem services. As RSCs are often located in close proximity to developed areas, such ecosystem benefits can be directly realized by surrounding communities. Chapter 6 presents a chronosequence of 14 sites varying from 1 to 14 years old were assessed for the presence and extent of select ecosystem service indicators. Soil carbon accumulation, microbial biomass carbon, and habitat provision significantly increased as RSCs established over time. Biodiversity and cultural benefits are most evident in RSCs when recreational and educational infrastructure, plantings, and wet areas are incorporated into RSC design. Overall, ecosystem services provided by RSC are similar to or exceed those demonstrated in constructed stormwater wetlands in all aspects except cultural benefits.

Research has shown that RSCs and other nature-based stormwater control measures (SCMs) can provide some level of healthy ecosystem function in urban areas. At the same time, decades of research support the need for access to nature for healthy childhood development. Designing and locating nature-based stormwater systems where children frequent renders systems as multi-functional spaces, providing synergetic opportunities, which benefit individuals and communities. Chapter 7 presents such an argument for incorporating SCMs into childhood play spaces. Challenges to integrating these spaces include safety, cost, and

management, all of which can be overcome by smart and appropriate design. Such design requires collaboration between different skillsets and stakeholders through some minimal, but essential changes in the consultation and design process. Ultimately, integrating nature-based stormwater practices into children's outdoor spaces will provide economic, environmental, and social benefits to urban areas.

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Quantifying the Stormwater Mitigation Performance and Ecosystem Service
Provision in Regenerative Stormwater Conveyance (RSC)

by
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DEDICATION

To Peter Bosscher, who, through his own life, awakened in me the calling of
Christian vocation as an engineer

BIOGRAPHY

Adrienne Rose Cizek was born on February 18, 1983 in Sheboygan, WI to Tom and Nancy Kuehl. She and her brother, Matthew, were raised in a region of south central Wisconsin known for its bountiful clear lakes and rocking rolling glacial formations.

As a child, Adrienne and her family enjoyed camping, hiking, and biking. Most of her childhood was spent exploring the outdoors with neighborhood friends. Upon beginning her undergraduate education at the University of Wisconsin – Madison, Adrienne knew she was good in math and science and interested in finding a balance between environmental preservation and the ever-growing human needs, although the capacity by which she would do this was unclear.

It wasn't until the beginning of her junior year at Madison that Adrienne got to know several professors through Geneva Campus Church. These professors were able to share with her, both through their lives and their words, the call of Christians to a life vocation that actively brings about God's kingdom. One of those professors, Peter Bosscher, worked in the engineering department and led the university chapter of Engineers without Borders. That same year, Adrienne became an aspiring environmental engineer, and spent a month in a small village in Rwanda implementing a drinking water pipe network. She also worked in the University's pilot water treatment lab on experiments treating *cryptosporidium parvum*. She graduated with her engineering degree in 2006, and subsequently married fellow UW graduate, Paul Cizek.

The two moved to North Carolina, where Adrienne pursued her Master's degree in environmental engineering at the University of North Carolina – Chapel Hill. Her master's research, under the guidance of Greg Characklis, investigated the effectiveness of removing *cryptosporidium parvum* and *giardia* via coagulation from

New York City's drinking water reservoirs. She continued to be active in UNC's chapter of Engineers without Borders, and implemented a drinking water network in Ciudad de Dios, Peru during the summer of 2007. Upon graduation in 2008, she began working as an engineer at a small innovative company designing landscaped gardens and terraces for wastewater and stormwater treatment and reuse.

In late 2009, Adrienne was introduced to Dr. William Hunt through his progressive work in stormwater engineering with the state of North Carolina. She began her doctorate studies at North Carolina State University under Dr. Hunt in January, 2011, when her first daughter, Geneva, was 5 months old. Her studies focused on stormwater mitigation performance and additional ecosystem services provided by a new nature-based stormwater control measure called regenerative stormwater conveyance. In April 2011, Adrienne was awarded the EPA STAR fellowship to complete her studies. During her time at NCSU, Adrienne participated in stormwater extension workshops, while also dabbling in landscape architecture. She worked on an independent study under Andrew Fox with the Natural Learning Initiative focused on designing stormwater structures in childhood play spaces for the benefits of both environmental restoration and childhood development – a perfect combination of interests for this engineer and mother of two.

Upon completion of her Ph.D., Adrienne is working with Stormwater Solutions Engineering in Milwaukee, WI, teaching courses at the UW-Milwaukee School of Continuing Education, and serving as the technical advisor to the stormwater wetland/outdoor classroom at Lake Country School in Hartland, WI. She is continuing to work towards her professional engineering licensure. Her long-term goals include collaborative work on innovative stormwater and green infrastructure solutions, while also providing multifunctional valuable spaces for people in urban and suburban environments.

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Many people have supported me on this journey. Of course, Paul has played many roles (i.e., caring husband, cheerleader, cook, childcare giver, etc.), but his most noticeable role has been that of “accountability”. He reminded me to keep my focus on that of God’s kingdom, and not get caught in the details of academia, pollutant loads, and macroinvertebrates. He has helped me think through and articulate many aspects of life and work through the Christian narrative. He encouraged and modeled a rhythm of life that was the only way to sustain graduate work while parenting, one that included both hard work and rest. Paul, I hope I can provide you with the same support as you begin your graduate work.

My parents gave me a wonderful childhood, full of love and stability. They supported and encouraged me in all my decisions, even when they would not have made them themselves. They have provided the support we needed in tight times, including extended childcare and, most recently, housing. Possibly most important, they have let me be my own person and loved me for it. Thank you mom and dad for the love and support you continue to show my family and me.

Dr. Hunt took a risk on a nontraditional student, and I hope he has not been disappointed. Not only did he guide me professionally, he also supported me in my life as mother. I am confident that this is truly unique in an advisor, and I do not think I would have begun this degree if he had not been so from the beginning. Bill, thank you infinitely for this support, and Julia, for opening up your home and family to us.

There are also many people who have encouraged and mentored me as a Christian throughout this journey. Friends and families from Geneva Campus Church and Holy Family have formed me and my family in so many ways – and I will carry your

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1. Introduction

Healthy aquatic ecosystems are essential for promoting and sustaining human life. However, human development has converted land from natural ecosystems to urban and suburban land uses. Urban areas are associated with a high degree of impervious surface, resulting in large volumes of stormwater runoff and associated pollutants entering nearby waterbodies. Stormwater runoff has detrimental effects on ecosystem function. Low impact development (LID) strives to maintain predevelopment (native) hydrologic conditions on developed lands. A new LID stormwater control measure (SCM), referred to as regenerative stormwater conveyance (RSC), uses principles of stream restoration to treat and manage stormwater prior to it entering receiving waters. In addition to the stormwater treatment benefits, RSC appears to provide a suite of additional ecosystem benefits. RSC may offer potential to serve as nature pockets in urban and suburban areas.

1.1 Ecosystem Services

Human populations derive essential benefits, both directly and indirectly, from the natural ecosystems around them. These benefits, referred to as *ecosystem services*, substantially influence all components of human wellbeing, including basic material needs, health, good social relations, and security (MEA, 2005a).

Ecosystem services can include provisioning, regulating, cultural, and supporting services (Figure 1-1). Biodiversity is both an effect of healthy ecosystem function and a service in itself, as it underpins the provision of many other services (de Groot, 2006). Aquatic ecosystems, such as wetlands and streams, are especially important to human wellbeing. Costanza et al. (1997) estimates global freshwater aquatic ecosystems to account for nearly \$6.6 trillion annually, through gas regulation, climate regulation, land disturbance protection, water supply and regulation, waste assimilation, habitat provision, food and raw material provision, and cultural and recreational benefits. Services provided by aquatic ecosystems are both dependent and interdependent on the health of the ecosystem as a whole (Costanza et al.,

1997). Due to urbanization, many of these systems and the services they provide are being lost or compromised (MEA ,2005a). This is a growing problem, as more than 60% of the world's population is expected to live in urban areas by 2030 (UN, 2005).

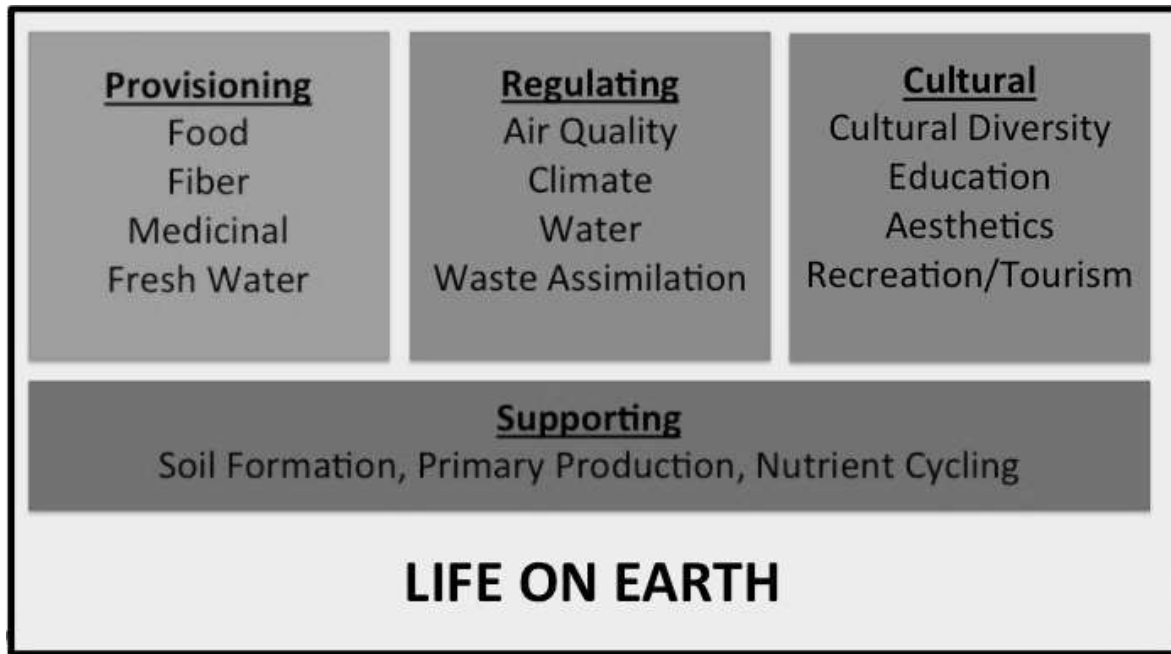


Figure 1-1 Ecosystem services categories and examples

1.1.1 Valuation of Ecosystem Services

Most land is valued by its potential market value. For example, a forest may be valued for the wood it produces, which humans use for building. However, forests also provide clean water, clean air, climate regulation, and more commodities not yet marketed. Recently, efforts have gone into estimating the non-market values to different ecosystems services. In many cases, the non-market services are estimated to be more valuable than market value (MEA, 2005a). Costanza et al. (1997) estimated the value of global ecosystem services to be \$33 trillion annually,

with wetlands and streams/lake providing \$23K of services per hectare annually. Even if the values that Constanza et al. (1997) estimated were off by a factor 100, conservation, restoration, and preservation of ecosystems would still make economic sense (Balmford et al., 2002). On a smaller scale, McPherson et al. (1997) estimated that the net present value (NPV) of services provided by urban trees in Chicago is \$402 per planted tree, more than twice the cost of the trees themselves. Loomis et al. (2000) performed a willingness to pay survey in regards to restoring a segment of a river in an impaired river basin which would increase water quality, provide erosion control and wildlife habitat, and improve recreation. The survey found that the community valued these ecosystem services at \$19 million to \$70 million annually, the lowest of which was still greater than the costs of improving the stream segment. Therefore, the additional value added by improving ecosystem function for different land use options (often not considered) should be incorporated into economic basis for land use planning and design.

1.1.2 Natural and Engineered Ecosystems

Current regulation suggests that restored and engineered ecosystem will provide ecosystem service to the same degree as natural ecosystems (i.e. wetland mitigation under Section 404 of the Clean Water Act (CWA)). However, studies show that certain ecosystem benefits are established earlier and more fully than others, and some services may never fully establish. A chronosequence of constructed *spartina alterniflora* marshes have provided a consistent narrative for ecosystem establishment (Craft et al., 2002; Craft et al., 1988; Craft et al., 2003; Craft et al., 1999). This series of studies reported that physical processes related to hydrology established in first five years. Primary production and biological processes strongly linked to primary production, as measured in biomass production and invertebrate populations, become similar to those of the natural marshes in years three to 15. Finally, soil structure and composition is observed as soon as 15 years, but often not at all. Planted cordgrass marshes, restored to provide habitat for the endangered light-footed clapper rail, were unsuccessful in providing long enough

grass stems for the bird's nesting practices (Zedler, 1993). On the other hand, an eleven-year-old reclaimed riverine forest in Florida showed plant species and soil characteristics largely similar to those in a nearby reference site (Clewell, 1999).

Ecosystem-based SCMs can provide some ecosystem services to urban and suburban areas including climate regulation, biodiversity, and recreation and education opportunities. Carbon sequestration, flora and fauna biodiversity, and cultural benefits were present in engineered stormwater wetlands in North Carolina, although not to the extent observed in natural wetlands (Moore and Hunt, 2012). On the other hand, Bishop et al. (2000a) found low to moderate species richness in stormwater wetponds in Toronto, Canada, indicating that wetponds do not provide a high quality habitat for wildlife. Bouchard et al. (2013) found that vegetated roadside swales increase in soil carbon concentration for the first 20 years, and then stabilize. Wetland swales have higher areal soil carbon concentrations than conventional grassed swales. Costanza and Daly (1992) suggest that an ecosystem must have a minimum level of ecosystem infrastructure to allow production of the total range of services. It is, therefore, further research is necessary understand the extent to which SCMs to provide ecosystem services to supplement or replace natural ecosystems in urban and suburban areas.

1.1.3 A Call for Action

Urbanization has both directly and indirectly altered surrounding natural ecosystems to the point where they are unable to provide the fullest extent of essential ecosystem services. Important drivers of these alterations to ecosystems are habitat change, overexploitation, invasive species, pollution, and climate change (MEA, 2005a). The Millennium Ecosystem Assessment report (MEA, 2005a) proposed the integration of ecosystem management into a broader developing framework. One example of this is designing stormwater infrastructure with more holistic objectives beyond just that of water quality and volume control. Nature-based SCMs inherently

depend on ecosystem function to mitigate stormwater pollution and may offer more services than what they are given value for.

1.2 Urbanization and Pollution

Population of urban areas in the world is estimated to be 4.9 billion by 2030, more than quadrupling since 1950 (UN, 2005). As urban populations increase, the amount of land required to sustain them also increases. Folke et al. (1997) found that cities in Baltic Europe require land area 500 to 1000 times larger than cities themselves for resource production and waste assimilation. This means that, despite the fact that urban areas only account for 2% of the land area (Grubler, 1994), additional land must be altered to provide for the needs (and wants) of these dense populations (Lambin et al., 2001). These land-use changes – urban, suburban, and supporting - disturb the native vegetation and soil structure, resulting in increased stormwater runoff and pollutant loads.

1.2.1 Stormwater Pollution from Urbanization

Klein (1979) identified major factors affecting stream quality to include reduced base flow, alteration in the natural stream temperature regimen, alteration of the character and energy of inputs, increased entry of toxic substances, and elevated nutrient inputs, all of which can result from stormwater runoff from urbanized landscapes. Urbanization has: 1) destroyed ecosystems that naturally mitigate stormwater and associated pollutants (Bernhardt and Palmer, 2007); 2) increased the degree of imperviousness resulting in an increased amount of stormwater runoff volume, flow, and duration (Bernhardt and Palmer, 2007; Arnold and Gibbons, 1996; Walsh et al., 2005; NRC, 2009); and 3) contributed additional pollutants, such as nitrogen, phosphorus, fecal bacteria, or heavy metals, to the environment to ultimately be transferred by runoff into receiving waters (Bennett et al., 1999; Waschbusch et al., 1999; Passeport et al., 2009; Hathaway and Hunt, 2011). The culmination of these things has detrimental effects on surface waters and ecosystems across the globe.

1.2.1.1 Loss of Natural Stormwater Mitigation

Vegetation and biological activity in undeveloped watersheds support a highly porous soil structure allowing for infiltration. The organic matter in the soil helps reduce erosion of small particles and holds moisture in the soil. Consequently, in an undeveloped watershed, stormwater is either infiltrated or evapotranspired for all but the most intense storm events (NRC, 2009). In contrast, developed or supporting lands are often stripped of their vegetation and topsoil and compacted for construction or agriculture purposes. Even “green space” in developed areas have reduced infiltration rates. Pitt et al. (2002) found that nearly one third of urban soils tested in Milwaukee, Wisconsin had infiltration rates of nearly zero. These combined effects resulting in a developed landscape with little to no natural ability to mitigate stormwater.

1.2.1.2 Imperviousness

Impervious surface cover is often classified as pavement or rooftops, where water is unable to infiltrate. However, as described by Pitt et al. (2002), compacted green spaces currently regarded by stormwater models as pervious, can be virtually impervious as well. The reduction or elimination of infiltration into the soil results in larger volumes of runoff entering receiving waters. In the case where the receiving water is a stream, the larger volumes increase the stream velocity causing severe erosion and incision, which eventually lowers the water table around the stream (Groffman et al., 2003). Additionally, flow over impervious surfaces is more efficient such that runoff travels to receiving water faster (NRC, 2009). The increase in runoff volumes and peak flows, combined with the decrease in time of concentration causes rapid fluctuations in streams levels and higher chances of flooding.

Higher stream flow velocities also result in increased sediment transport. The transport capacity within a stream increases non-linearly with flow velocity such that a small increase in stream velocity will result in a larger increase in transport capacity (Vogel et al., 2003). When the amount of sediment entering the stream is

smaller than the amount of sediment being transported through stream (often the case with stormwater from concrete or rooftops), then incision, or down cutting, occurs (Groffman et al., 2003; Booth, 1990; MacRae, 1996). Incision is especially characteristic in older, stable urban and suburban developments with few sources of sediment to replace that scoured from the stream (Groffman et al., 2003). Incision lowers the elevation of the streambed, and in turn lowers the base flow and ground water level along the stream. The effect, groundwater drought, harms vegetation in the riparian zone, decreasing further this zone's ability to prevent movement of pollutants, such as nitrate, from uplands into the streams (Groffman et al., 2003). Increased velocities and incision also limit opportunities for in-stream nutrient removal (Bukaveckas, 2007; Galloway et al., 2004). Altogether, urbanization has a profound effect on stream geomorphology and hydrology, which ultimately affect the stream function and ability to provide ecosystem services.

1.2.1.3 Pollutants

Urban land-use changes are often associated with increases in pollutant loadings. Nitrogen and phosphorus loadings are high in runoff from agricultural lands. However, these nutrients are also found in runoff from urban and suburban land uses in concentrations nearly a magnitude greater than in runoff from forested landscapes (NRC, 2009). Urban sources of nitrogen, namely fossil fuel combustion, play a major role in increased nitrogen concentrations in coastal areas through atmospheric nitrogen deposition (NRC, 2000). Anthropogenic nitrogen fixation has increased 2- to 3-fold over the past 40 years, and continues to grow (Galloway et al., 1995). Stormwater runoff from roadways and commercial land uses contribute annual lead, copper, and zinc loadings of approximately 3, 0.4, and 2 lbs/ac, respectively, into receiving waters (Burton and Pitt, 2001). Additionally several studies have measured indicator organism concentrations, as well as pathogens, in stormwater runoff from urban and suburban land uses well above the EPA recommended limits (Hathaway and Hunt, 2011; Cizek et al., 2008; Krometis et al., 2011). The additional pollutants entering receiving waters, combined with the

degradation of natural system's ability to mitigate pollutants, have detrimental consequences for public and ecosystem health.

1.2.2 Stream Health and Impervious Cover

Klein (1979) studied 27 small catchments in the Piedmont province of Maryland and identified impervious surface cover as a reliable indicator of stream degradation. Since then, many studies have agreed with Klein's findings, and also suggest that stream quality consistently drops from good to fair when the watershed impervious cover reaches 10-15% (Arnold and Gibbons, 1996; MacRae, 1996; Walsh, 2000; Wang et al., 2000; Schleuler, 1994; Paul and Meyer, 2001). Arnold and Gibbons (1996) found associations between streams labeled as "degraded" and impervious cover greater than 30%. Several other studies argue that, although imperviousness is important, how impervious surfaces are connected to the receiving waters determines the severity of the degradation (Hatt et al., 2004; Taylor et al., 2004; Walsh et al., 2004; Newall and Walsh, 2005). Directly connected impervious area (DCIA), or impervious surfaces that directly drain to receiving waters (i.e. via pipe, curb, etc.), transfer more runoff and associated pollutants than impervious surfaces that drain to impervious surfaces prior to entering a receiving water. Although disconnecting impervious areas may reduce the impact of imperviousness on stream health, Miltner et al. (2004) ultimately showed that few sites with greater than 27% total impervious area can meet interim CWA goals.

1.2.3 Effectiveness of SCMs on Stream Health

Several studies of the past 30 years have shown decrease in macroinvertebrate diversity with increasing imperviousness (Klein, 1979; Walsh et al., 2005; Hogg and Norris, 1991; Walsh, 2000; Roy et al., 2003). In a study performed examining benthic macroinvertebrate indices in small streams of three regions (Maryland, Texas, and Washington), Horner et al. (2003) showed that high urbanization and loss of natural cover *always* led to biological degradation. Increased runoff volumes and velocities associated with urbanization alter the sediment distribution with

receiving streams, causing decline in macroinvertebrate populations (Roy et al., 2003). Observations of fish species decline have also been associated with the urbanization of watersheds (Klein, 1979; Horner et al., 2003; Wang et al., 2000).

SCMs are designed to mitigate the increased runoff loads associated with urbanization in order to protect receiving water. Stormwater management strategies have shifted from flood control by diverting runoff via pipe networks to designing systems which attempt to treat pollutants and reduce runoff volume and peak flow by providing opportunity for infiltration and evapotranspiration (NRC, 2009). Horner et al. (2003) examined how structural SCMs could moderate the effects of urbanization on stream health, using a macroinvertebrate index as an indicator. The study concluded that highly urbanized watersheds showed considerable improvements with SCMs, however, there were no instances of high macroinvertebrate indices (>75%). Ultimately, SCMs may be able to shift the impervious cover thresholds mentioned previously, but current development practices will continue to degrade streams. It should be noted that this study did not include low impact development or nature-based SCMs, which aim to match pre-development hydrologic conditions, and may therefore, better preserve receiving stream integrity.

1.2.4 Urbanization and Public Welfare

Increases in stormwater runoff pollution are a concern to the public. Public safety and welfare concerns associated with severe incision include steep, unstable stream banks and flashy stream levels leading to frequent and unpredictable flooding. Public health is also a concern, as beaches are often closed due to high fecal bacteria concentrations. Water related disease outbreaks in the United States are often associated with extreme precipitation (Curriero et al. 2001; Gaffield et al. 2003). Furthermore, ecosystem degradation can be costly to municipalities and industry. Beach closings and restricted fishing are often a consequence of large rainfall events in coastal areas (Ajuzie and Altobello, 1997). New York City's drinking water supply

located pristine Catskill Mountains is under threat as upstream development increases, despite a 28,000 hectare (ha) conservation easement (DePalma, 2006).

1.3 Stormwater Control Measures for Urban and Suburban Areas

Until recently, the goal of stormwater management was flood control for public safety. However, a series of regulations, beginning with the Clean Water Act in 1972, provided the foundation for conventional stormwater management that we see today, with an emphasis on water quality and peak flow mitigation. Most recently, emerging low impact design (LID) strategies are emphasizing stormwater control measures that reduce runoff volume by aiming to achieve predevelopment hydrology on developed sites.

1.3.1 Evolution of Regulations

The recognition of the stormwater runoff contribution to waterbody impairment is very recent - within the past 30 years. The Clean Water Act (CWA) of 1972 set the goal of restoring and maintaining chemical, biological, and physical integrity of the nation's water bodies through the National Pollutant Discharge Elimination System (NPDES). This set precedence for taking inventory of pollutant sources for currently impaired water bodies by establishing a pollutant total maximum daily load (TMDL). Implementation of the TMDL program began at the state level during the 2000's. As TMDLs got underway, it became evident that waterbody impairment is often dominated by non-point pollution sources, as opposed to the point discharge pollution sources monitored under the NPDES permitting (NRCS, 2009). As a result, the last decade of stormwater management has been focused on controlling non-point stormwater pollution through structural and non-structural SCMs.

1.3.2 Stormwater Management Goals

The CWA of 1972 shifted the focus of stormwater management from flood control to pollutant removal. Permits were issued with limits on water quality. Although runoff volume is often considered under these permits, it is only used as a surrogate for

water quality (NRC, 2009). Consequently, SCMs are chosen based on their pollutant concentration reduction (i.e. wet pond achieve 85% TSS removal credit according to the 2009 North Carolina Department of Water Quality (NC DWQ) Stormwater Best Management Practices Manual). Throughout the past decade there has also been a growing approach in stormwater engineering called low impact development (LID). LID allows for the development of a site while maintaining pre-development hydrology. In 2007, the Energy Independence and Security Act (EISA) required all federal development and redevelopment projects of 465 m² or larger to achieve pre-development hydrology to the “maximum extent technically feasible” (Energy Independence and Security Act, 2007). As the stormwater engineering field moves towards hydrology driven mitigation (Low Impact Development Center, 2007), it becomes imperative to understand what constitutes pre-development hydrology, and how to best achieve it.

1.3.3 Stormwater Control Measures

Managing stormwater on a site is generally achieved by piece-working several different types of SCMs together. For the sake of this paper, the SCMs can be categorized as those that focus on 1) peak flow attenuation, 2) stormwater conveyance, and 3) runoff volume reduction. As the field is progressing towards designing systems to achieve pre-development hydrology, SCMs which focus on reducing runoff volume will be given the most attention as they have the greatest potential to meet this goal.

1.3.3.1 Peak Flow Attenuation

An example of a peak flow attenuating SCM is the detention/retention basin (wet or dry). These basins are designed to capture the runoff from a site and slowly release it through an outlet structure over the course of two to five days. By having controlled release of the runoff, detention basins are able to reduce downstream erosion that would result from high velocity flows characteristic of impervious areas. Although these structures effectively regulate large flows and achieve some degree

of treatment (Geosyntec Consultants and Wright Water Engineers 2008), they offer little improvement to, and may actually worsen, watershed scale flooding (NRC, 2009), as there is virtually no overall volume reduction (Geosyntec Consultants and Wright Water Engineers 2011). Despite demonstrating excellent water quality mitigation and a suite of ecosystem benefits (Moore and Hunt, 2012), wetponds act similarly to detention/retention basins in that they often do not effectively reduce overall runoff volume (Geosyntec Consultants and Wright Water Engineers 2011). Wetlands do offer some opportunity of meeting pre-development hydrology as they move water through several pathways within the system: the vegetated surface, the organic soil layer on the wetland ground surface, and potentially slow infiltration into the clay layer. Furthermore, stormwater wetlands are generally implemented for watersheds greater than 1.6 ha (Wossink and Hunt, 2003), and therefore, often do not receive highly urban runoff flows directly.

1.3.3.2 Conveyance

Conveyance structures in urban areas have traditionally consisted of pipes, which efficiently moving water from a collection point to a waterbody. In this case, stormwater runoff undergoes no treatment or volume reduction. In many urban areas, new construction is required to treat stormwater runoff onsite prior to discharge (often via pipe) into streams. Outside of dense urban areas, swales are a less expensive and more beneficial option for conveying stormwater. Swales are vegetated channels (often grassed) that direct runoff towards an endpoint. Swales are able to provide some treatment from smaller storms by maintaining a water level during flows below the grass height (hence, achieving a level of vegetated filtration). Sedimentation, exfiltration to parent soils, soil surface chemical treatment are also possible pollutant removal mechanisms. Deletic and Fletcher (2006) examined an artificially dosed grassed swale in Brisbane, Australia. Their results showed good removal of TSS for a variety of flow rates: 85% and 65% removal for inflow rates of 2 and 15 L/s, respectively. The study also showed an exponential relationship

between nutrient removal and 65 meters of swale length, achieving an overall removal of 46% and 56% for TP and TN, respectively.

As the treatment of runoff is becoming more and more important, especially in nutrient sensitive waters, researchers and engineers are examining ways to enhance the performance of swales. Yu et al. (2001) examined swale performance in Taiwan and Virginia. With check dams in place, removal efficiencies increased from 48% to 70%, 14% to 21%, and 29% to 77% for TSS, TN, and TP, respectively. The check dams increase the hydraulic residence time and decrease velocity. Winston et al. (2012) compared the performance of grassed swales and wetland swales (swales located in soil with a high water table and are thus permanently submerged) along Interstate-40 in North Carolina. Although concentrations of TSS and TP were similar between wet and dry swales, the wetland swales showed statistically significant lower concentrations of TN being exported. Thus, in areas with high water tables, wetland swales may be used to further reduce nitrogen loadings from stormwater runoff. The swales examined in the NC study did not show any significant exfiltration, likely due to the high degree of compaction during construction.

1.3.3.3 Volume Reduction

Many studies have shown that increased runoff from urban areas causes increased pollutant loads, erosive discharge and stream velocities, and a drop in groundwater level and stream base flow level (Geosyntec Consultants and Wright Water Engineers, 2011; USEPA, 2009). Recently, efforts have been made to understand the hydrology occurring in SCMs, in particular, how well SCMs are able to reduce runoff volume (Geosyntec Consultants and Wright Water Engineers, 2011; Brown et al., 2010; Li et al., 2009). As the increased impervious surfaces associated with urbanization reduce evapotranspiration and infiltration into parent soil, SCMs that encourage exfiltration and evapotranspiration are able to reduce the overall runoff

volume leaving the watershed. Furthermore, the focus on exfiltration, even shallow exfiltration, offers some opportunity for achieving predevelopment hydrology.

Bioretention is an excellent example of a SCM that promotes both exfiltration and evapotranspiration. A bioretention cell is composed of vegetation and mulch over a bed of porous media. Runoff passes through the media bed and then exits through under drain pipes. Davis et al. (2012) studied the hydrology of three bioretention cells in Maryland, North Carolina, and Pennsylvania. All three cells reduced outflow as compared to inflow into the cell, such that only 23%, 14%, and 48% of the inflow volume was discharged at each of the sites, respectively. These results suggest that there are additional losses in the water budget, most likely exfiltration and evapotranspiration. In examining six existing bioretention cells with different design parameters, including varying media depths, ponding depths, and surface to drainage ratios, throughout Maryland and North Carolina, Li et al. (2009) saw consistent trends in peak reduction, peak delay, and outflow duration. Peak flow reduction occurred at all six sites, with a minimum reduction of 94%. Over 70% of the events tested met the peak flow target criteria described by Davis (2008) (i.e. ratio of time of peak outflow and peak inflow is greater than six). The outflow target (less than 1/3 of the inflow runoff volume discharged from the site 24 hours after peak) was met 40% of the time. A shallow bioretention cell with a liner inhibiting exfiltration achieved this goal only 15% of the time.

Hunt et al. (2006) studied several bioretention cells in the Piedmont, North Carolina. The cells demonstrated seasonal variation in their ability to reduce runoff volume, with a mean 93% volume reduction in summer and a mean 46% volume reduction in winter. As higher evapotranspiration rates occur in summer, this variation suggests that evapotranspiration plays an important role in removing runoff from the bioretention cell itself. Nitrogen loads exiting the cells were reduced up to 75%, primarily due to the reduced runoff volume. Hunt et al. (2008) showed reductions in

nutrient and TSS concentrations between 31% and 73% in a bioretention cell in Charlotte, NC. Thus, in addition to reducing overall runoff volume, bioretention cells also shows evidence of decreasing pollutant concentrations, as well as attenuating peak flows for small and medium size storm events.

1.4 Regenerative Stormwater Conveyance

Regenerative stormwater conveyance (RSC), also described as biofiltration conveyance (BFC) by NC Dept. of Transportation and step pool stormwater conveyance (SPSC) by MD Dept. of the Environment, are open channel conveyance consisting of a porous sand media bed, riffle/weir step pools, and vegetation. Unlike most other SCMs, these systems are considered regenerative, in that they provide a positive feedback supporting surrounding environments, such that as the system establishes the surrounding environment is improved, hence further improving the system. Although limited data exists on RSC performance (none of which is peer-reviewed), preliminary data show that the systems offer some degree of typical stormwater management criteria, including peak flow attenuation, water quality treatment, conveyance, and runoff volume reduction.

1.4.1 Regenerative Systems

Conventional approaches to engineering have detrimentally impacted the environment, as described previously. These impacts are recognized, and in an effort to stop and reverse them, engineering design can take on several design philosophies from solely reducing impacts to actively promoting living systems. Regenerative design requires examining and engaging the system as a whole, such that all aspects of the system are integral to the life process and evolution of the system. When this occurs, the design process functions as a catalyst for evolutionary change (Integrative Design Collaborative et al., 2006), such that all parts of the systems are able to grow and adapt, supported by the remaining parts of the system (positive feedback). In order to design regeneratively, an interdisciplinary effort must be made to articulate the project objectives and

understand the broader context of the ecosystem. For example, Walter and Merritts (2008) show that natural stream beds throughout the eastern United States prior to colonial settlement actually consisted of branching channels within extensive carbon-rich vegetated wetlands, as opposed to the gravel bed meandering streams bordered by a self-formed fine-grained floodplain that typically drive stream restoration. In understanding this, ecological engineers are able to alter the river restoration approach to include a base flow channel highly incorporated with its floodplain, aided by a series of pools and weirs (Berg, 2009). Additionally, regenerative systems depend entirely on the quality of their ecosystem function, such that ecosystem services in regenerative systems will demonstrate ecosystem services beyond that of stormwater mitigation. Stormwater engineers are able to use this knowledge in order to more holistically and regeneratively design stormwater conveyance as zero-order ephemeral stream ecosystems.

1.4.2 RSC Components

RSC, being ecosystem-based, are specifically engineered to achieve predevelopment hydrology. Water is expected to exit the system as seepage out for smaller storms, and as non-erosive surface flows for extreme floods (up to the 100-yr storm event) (Brown et al. 2010; Flores et al. 2009). Specific RSC components are required to achieve these goals – sand bed material, riffles and pools, and an established plant community (Figure 1-2). Each component offers opportunities for hydrologic and water quality improvement.

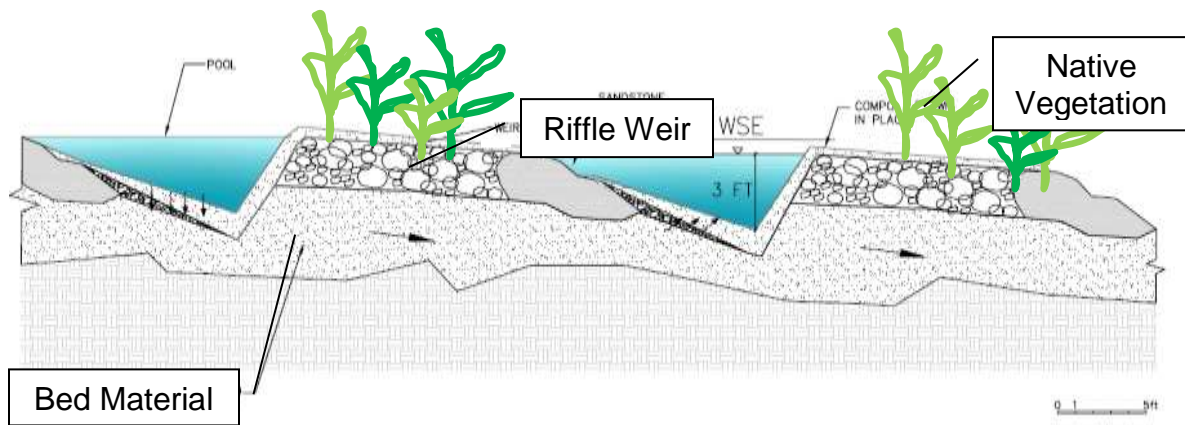


Figure 1-2 Profile view of possible RSC system, including bed material (sand), riffles and pools, and native vegetation (Image courtesy of Biohabitats, used with permission).

1.4.2.1 Bed Material

The bed material, located below the riffles and pools (Figure 1-2), is designed to have a high hydraulic conductivity such that runoff will easily infiltrate from the pools into the media bed. In this way, the runoff will

- 1) Undergo media filtration removing sediment and associated pollutants,
- 2) Be stored in the media pores, reducing and possibly eliminating the need for downstream detention (Berg and Underwood, 2009),
- 3) Seep through bed material and into the parent soil, and
- 4) Recharge the groundwater.

Unlike bioretention, the carbon-rich bed material is an 80:20 to 70:30 blend of sand and shredded hardwood mulch. Therefore, the media bed is both highly porous and able to support fungal and microbial communities necessary for enhanced nutrient reduction (Berg and Underwood 2009).

1.4.2.2 Riffles and Pools

As with stream geomorphology, the surface of the system is composed of a series of riffles and pools (Figure 1-2) to dissipate surface runoff energy, and reduce depth and velocity. Water leaving the pools passes over the riffle section followed by a parabolic weir. By slowing down the water, RSCs achieve

- 1) Non-erosive flows,
- 2) Sedimentation of solids and associated pollutants within the pools, and
- 3) Opportunities for thick vegetation growth, offering for further water quality treatment, habitat, and aesthetics.

As runoff volumes increase, the weirs direct the flow horizontally, as opposed to increasing the stream depth, which allow treatment mechanisms to occur as they would in a stream floodplain (Kaushal et al. 2008). Additionally, the pools temporarily store water and, therefore, reduce or eliminate downstream detention needs.

1.4.2.3 Established Plant Community

An established plant community is also important to the regenerative characteristics of RSCs. Plants offer a variety of opportunities for runoff volume and pollutant removal by

- 1) Providing a site for microbial activity and, therefore, nutrient reduction,
- 2) Taking up nutrients for plant growth,
- 3) Long term carbon sequestration through healthy root mass, and
- 4) Evapotranspiration

Additionally, thriving plant communities improve the aesthetics of a site by adding shade, privacy, and color. A plant community also provides the opportunity to restore a range of site ecologies.

1.4.3 Costs

Anne Arundel County in Maryland (MD) estimates that the majority of traditional stormwater conveyance devices throughout their county, including pipe outfalls and rip-rap/gabion level spreaders, have failed, costing the county more than \$600 million in damage (Brown et al., 2010). As an alternative to such devices, Anne Arundel County is interested in the potential of RSCs as SCMs. At a medium density residential site, Preserve at Severn, the installation of an RSC saved the developer approximately \$400K, more than half of the cost of using conventional storm drain pipe or other related drainage infrastructure (Brown et al., 2010). In addition to the capital savings, RSCs are easy to maintain, requiring only invasive plant management during the first five years and excess debris removal (Flores et al., 2009). Overall, RSC systems are potentially a less expensive and highly beneficial alternative to traditional stormwater control management practices.

1.4.3 RSCs as SCMs

Although RSCs are now a credited SCM in MD (MD DOE, 2014), very little data is available on their stormwater mitigation performance. Hydrologic TR-20 modeling of an RSC site receiving runoff from 7.2-ha of low-density residential development in Anne Arundel County showed a four-fold reduction in peak flow (Brown et al., 2010). Field scale stage monitoring of another RSC receiving water from a 5.7-ha medium-density residential neighborhood in the same area saw up to 50% reduction in peak flow throughout the RSC for rainfall events less than 3.8 cm (1.5 in) (Filoso, 2013).

Documented water quality performance in RSCs is limited to non-peer-reviewed reports. Filoso (2013) compared RSC performance to a control headwater stream in a neighboring watershed. TSS concentrations exiting the RSC were 60% less than the control stream, with median outflow concentrations of 20 mg/L. Total phosphate removal mirrored TSS removal. However, there was no overall difference in Nitrate-N (NO₃), Ammonium (TAN), total dissolved nitrogen (TDN), or total nitrogen (TN) outflow concentrations between the control stream and the RSC. Browning (2008)

monitored a flat, wet RSC in MD for her Master's research. She reported 0% to 50% TSS removal in the RSC, but with similar median outflow concentrations found by Filoso et al. (2013). In contrast to Filoso et al. (2013), this flat, wet RSC consistently reduced NO₃ and TAN by 20% to 40%, respectively, suggesting that a wetter system may provide more opportunities for nitrogen biotransformation (i.e. nitrification and denitrification).

In addition to the stormwater mitigation benefits, RSC systems have been reported as regenerative, in that they offer dynamic and diverse ecosystems for a range of plants, animals, amphibians, and insects, while also providing educational and aesthetic opportunities (Brown et al. 2010). RSC systems appear to be thriving, healthy ecosystems able to offer benefits towards the wellbeing of humans, while also achieving stormwater management goals at a lower cost.

1.4.4 Need for Further Research

RSCs appears to be a viable approach to stormwater management, both in terms of pollutant reduction and matching predevelopment hydrology. Further research is needed to determine the extent that these stormwater management objectives are met. Additionally, RSC systems are being advertised as nature-based systems, in that they appear to function, sustain, and regenerate healthy ecosystem function. Although, healthy ecosystem function has been observed in specifically designed habitat restoration applications (Underwood et al., 2006), these qualities have not been observed in the systems designed as SCMs.

1.5 Objectives

This research aims to

- i. Identify storm runoff pathways in undeveloped watersheds, and determine SCM characteristics necessary to match predevelopment hydrographs,
- ii. Monitor and characterize the hydrology of RSCs in the coastal plain and Piedmont eco-regions of North Carolina,

- iii. Evaluate the effectiveness of RSC as a SCM in terms of water quality and hydrology goals, and
- iv. Quantify and value additional ecosystem services provided by RSCs.

The result of this work will provide insight on the ability of RSC to achieve typical stormwater mitigation goals, while also providing the ecosystem services claimed of its regenerative design. Methods from this work can also be expanded to include other stormwater management technologies, and will aid engineers and decision makers in determining the appropriate stormwater approach for a given application. It is anticipated that this work will provide a cornerstone for interdisciplinary stormwater management in urban and suburban areas, where engineered systems are designed with more holistic objectives beyond just that of water quality and volume control.

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2. Defining predevelopment hydrology to mimic predevelopment water quality in stormwater control measures (SCMs)

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2.1 Abstract

As part of Low Impact Development, stormwater control measures (SCMs) are expected to mimic pre-development hydrology. This generally results in a comparison between outflow volumes discharged from SCMs and a target condition annual runoff. Such a simplistic evaluation overlooks multiple pathways of water present in target watersheds and SCMs, namely shallow interflow and groundwater surge. This discussion suggests a more refined means of evaluating cognate conditions for SCMs in terms of hydrology and effluent water quality by discretizing SCM discharge into three pathways: runoff, shallow interflow, and groundwater surge. Preliminary evidence using deuterium isotopes from bioretention outflow supports this concept, and future research routes are suggested.

2.2 Introduction

Stormwater pollution is a primary non-point pollution source of concern, and is linked to stream ecosystem degradation (Horner et al., 2003; Klein, 1979; Walsh et al.,

2004), economic loss (Ajuzie and Altobello, 1997) and public health issues (Curriero et al., 2001; Gaffield et al., 2003). Although water quality and stream health improvements are observed in conjunction with the implementation of stormwater control measures (SCMs, a.k.a. stormwater best management practices, or BMPs), stormwater pollution is still a leading cause of water body impairment (US EPA, 2011).

A recent paradigm in stormwater management includes designing SCMs to mimic predevelopment hydrology, as defined by undeveloped conditions. Conventional SCMs, such as wet ponds or dry detention basins, aim to damp peak flows. Although these structures effectively regulate large flows of runoff and achieve some degree of treatment (GeoSyntec and WWE, 2008), they offer little improvement to, and may actually worsen, larger watershed-scale flooding (NRC, 2009). A Low Impact Development (LID) approach to stormwater management focuses on designs which reduce/eliminate flow during small events and the first flush of moderate-sized events, where highest pollutant loading occurs, by promoting infiltration and evapotranspiration (ET) (Walsh et al., 2005; Liu et al. 2012). Achieving LID objectives would result in a similar hydrograph to that observed under undeveloped conditions (Davis, 2005; Chang, 2010). To be consistent with LID terminology, this paper uses the term *predevelopment hydrology* to describe hydrology observed under *undeveloped* conditions. Although decreased pollutant loading has been observed in conjunction with the achievement of predevelopment hydrology, very little research examines using the predevelopment hydrograph as a surrogate for achieving predevelopment water quality.

Focusing efforts primarily on the infiltration of stormwater runoff to meet water quality goals can prove difficult when soils have very low infiltration rates. Soils on developed sites show significantly lower infiltration rates than those on undeveloped

soils (Pitt et al., 2002; Gregory, 2006). Regions, such as the Triassic Basin in North Carolina and gumbo soils of East Texas, have underlying clay soils with naturally low infiltration rates. The predevelopment hydrograph, in such cases, will include overall larger volumetric contributions of runoff than an area with high infiltration rates. However, predeveloped conditions in clay underlying soils produce a higher degree of water quality than that observed under developed conditions (NC DENR, 2007). Predevelopment conditions, therefore, offer additional pollutant reduction mechanisms not considered when solely focusing on volume reduction.

Upon hitting the ground, rainwater will 1) flow across the surface as run off, 2) evaporate, 3) enter the top soil horizons and flow towards a stream as shallow interflow, or 4) infiltrate deeply into long term groundwater storage. Evidence suggests that surface runoff accounts for a small fraction of the contributing stream flow during a rainfall event. Williams and Pinder (1990) used stream flow data and ^3H isotopes for hydrograph separation to identify the pathways contributing to increased stream flow during and after a rain event. Analysis showed that contribution from surface runoff ended within 24 hours of the rainfall event, and yet streamflow was elevated above base flow for an additional 24 hours. The source of this additional streamflow is attributed to subsurface contributions, namely a groundwater surge and shallow interflow. Therefore, streamflow during a storm event, beyond baseflow, is actually comprised of water from three sources: 1) surface runoff, 2) shallow interflow, and 3) groundwater surge, with surface runoff comprising a small fraction (25% to 30%) (Brown et al., 1999; Kendell et al., 2001). This is contrary to the popular notion driving stormwater regulations that all water contributing to the storm hydrograph is surface runoff.

This discussion aims to better define predevelopment hydrology to achieve predevelopment water quality through stormwater control measures (SCMs).

Presented is a short literature review of 1) forested watershed (a predevelopment hydrologic condition) stream hydrograph fractions during storm events and 2) treatment mechanisms for nutrients along flow pathways in riparian zones. The objectives of such a review are three-fold: (i) determine the hydrograph fraction associated with each flow pathway to discretize the predevelopment hydrograph, (ii) predict treatment mechanisms for each pathway contributing to predevelopment water quality, and (iii) derive implications of flow pathways and associated treatment to stormwater management, specifically in terms of SCM function. The thrust of this discussion is predominantly theoretical, based on reviewed literature and preliminary data collection conducted by the authors. This serves as a stepping-stone for future research into SCM hydrograph separation such that predevelopment hydrology and associated water quality can truly be mimicked by engineered systems.

2.3 Defining Predevelopment Hydrology

2.3.1 Hydrograph Pathways

Hydrologic studies conducted in forested watersheds reveal three distinct pathways through which water enters a stream during a storm event: 1) surface runoff, 2) shallow interflow, and 3) groundwater surge. Within these pathways, hydrologists have identified event and pre-event water. Event water is from the rainfall event associated with the examined hydrograph. Pre-event water is associated with a previous rainfall event stored subsurface until discharged during a later event. Event water which enters the stream via overland flow during a rainfall event is aptly named surface runoff. Shallow interflow is composed of event water that has traveled through the upper soil horizons (Brown et al., 1999; Haria and Shand, 2006; Kendell et al., 2001). The groundwater surge is pre-event water forced into a stream during a rainfall event, beyond baseflow.

Hydrologic studies have reported a surge of groundwater (pre-event water) contribution to the hydrograph at the onset of a rain event (Haria and Shand, 2006;

Soulsby, 1995; Wenninger et al., 2004). The mechanisms of this surge are described by a pressure wave effect, where increased pressure gradients associated with the rainfall depth on the hillslopes induce a rapid reaction of groundwater levels near the stream (Beven, 1989; Haria and Shand, 2006; Wenninger et al., 2004). Due to topographic convergence, the hydraulic pressure upslope of the stream would need only increase a few millimeters to result in a relatively large discharge from the entire watershed (Bergmann et al., 1996, as written in Wenninger et al., 2004).

Ultimately, hydrograph separation studies tell a similar narrative: 1) rainfall occurs and event water infiltrates into the O- or A-horizon, generally a relatively permeable layer; 2) event water accumulates at the border of a less hydraulically conductive soil layer and creates a pressure wave which amplifies the pressure gradient and increases discharge of pre-event water into the stream; and 3) surface runoff and shallow interflow move relatively quickly downslope and into the stream.

2.3.2 Pathway Fractions with Hydrograph

Many studies on hydrograph separation during rainfall events performed in hilly or mountainous terrain found large fractions of pre-event water within the storm hydrograph (Brown et al., 1999; Soulsby, 1995; Wenninger et al., 2004). However, in areas of flat topography, such as the coastal plain of South Carolina, Williams and Pinder (1990) also found a large fraction of pre-event water (>90%) associated with the stream hydrograph, possibly as a result of the highly permeable soil reducing the fractions of surface runoff and shallow interflow. Variability in the pre-event water fraction has been linked to scale, with higher event water fractions observed in smaller watersheds (Brown et al., 1999). Despite variability among the literature, pre-event water composes the greatest fraction (at least 2/3) of the stream hydrograph (Table 2-1). Brown et al. (1999) measured the event and shallow interflow fraction at different points throughout the hydrograph. Significantly smaller

fractions of event water were observed prior to the peak flow, supporting the theory of an initial groundwater surge. Shallow interflow composed the highest fraction of event water beyond the peak of the hydrograph, and was the dominant source of water at the tail end of the hydrograph (Figure 2-1). Ultimately, under predeveloped conditions surface water composes a small fraction (25% to 30%) of the contributing storm hydrograph, with the largest fraction occurring prior to and during peak flow (Brown et al., 1999). In this way, the majority of the water entering receiving waters is subsurface contributions, having undergone a higher level of treatment.

Table 2-1 References investigating hydrograph separation fractions within stream hydrographs

<i>Reference</i>	<i>Location</i>	<i>Geological Region</i>	<i>Hydrograph Fraction</i>		
			<i>Surface Runoff</i>	<i>Shallow Interflow</i>	<i>Groundwater</i>
Brown et al. (1999)	New York	Catskill Mountains	25% ^a	10% ^a	65% ^a
Kendell et al. (2001)	China	Prairie, artificial watershed	30%	15% ^b 55% ^c	15% ^b 55% ^c
Soulsby (1995)	Wales	--		25%	75%
Wenninger et al. (2004)	Germany	Black Forest Mountains		20%	80%
Williams and Pinder (1990)	South Carolina	Coastal Plain		10%	90%

^a Average of the maximum event water and shallow interflow contributions over the course of all storms sampled

^b As measured using ¹⁸O isotope separation

^c As measured using SiO₂ concentrations

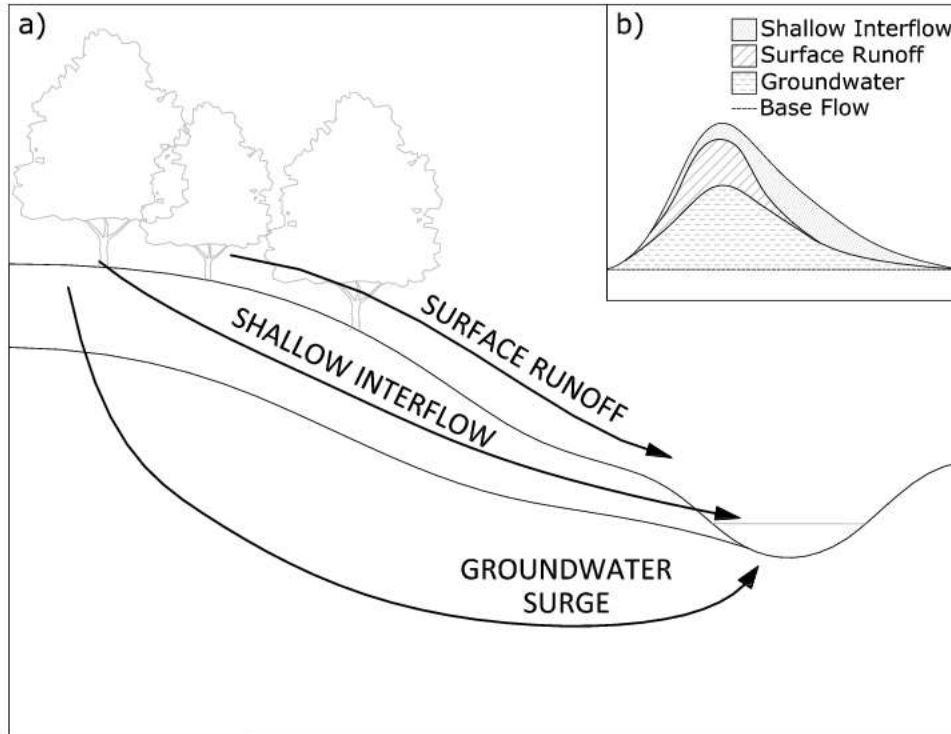


Figure 2-1 a) depiction of flow pathways experienced under predeveloped, or undeveloped, conditions, and b) example of stream hydrograph with contributing pathway fractions, based on data from Brown et al. (1999).

2.4 Treatment Mechanisms along Pathways

As water travels along each pathway, it undergoes some level of treatment. Each pathway offers a unique set of conditions allowing for a specific mechanism of pollutant removal. Treatment mechanisms observed along each pathway, in terms of nutrient (N and P) removal are described. Ultimately, nutrient reduction is possible to a very high degree, but removal is very specific to underlying soil. This review is an overview of the potential of removal for each pathway (Table 2-2)

Table 2-2 Potential nutrient removal associated with different treatment mechanisms within a riparian zone.

<i>Pollutant</i>	<i>Removal Mechanism</i>	<i>Potential Removal</i>	<i>Sources</i>
<i>Surface Runoff</i>			
NO ₃ ⁻	Adsorption/ Sedimentation	10% to 80%	Lowrance and Sheridan, 2005; Peterjohn and Correll, 1984; Verchot et al., 1997
TKN	Adsorption/ Sedimentation	35% to 60%	Daniels and Gilliam, 1996
PON	Sedimentation	85%	Peterjohn and Correll, 1984
TN	Adsorption/ Sedimentation	20%	Lowrance and Sheridan, 2005;
TP	Adsorption/ Sedimentation	10% to 75%	Daniels and Gilliam, 1996; Parsons et al., 1994
Sed-P	Sedimentation	75%	Lowrance and Sheridan, 2005;
<i>Shallow Interflow</i>			
NO ₃ ⁻	Denitrification	60% to 95%	Cooper, 1990; Cooper et al., 1995; McDowell et al., 1992; Jordan et al., 1993, Lowrance et al., 2000
NO ₃ ⁻	Plant Uptake	60%	Cooper, 1990
DON	Mineralization	70%	McDowell et al., 1992
NH ₄ ⁺	Ammoniazation	Increase	Peterjohn and Correll, 1984
TP	Filtration	33%	Peterjohn and Correll, 1984
DOP	Mobilization	Increase	Peterjohn and Correll, 1984
<i>Groundwater</i>			
NO ₃ ⁻	Denitrification	70% to 100%	Bohlke and Denver, 1995; Cooper, 1990; Jacobs and Gilliam, 1985; Lowrance et al., 2000; Puckett and Hughes, 2005; Weil et al., 1990
NO ₃ ⁻	Dilution	85% to 100%	Cey et al., 1999; Komor and Magner, 1996
NO ₃ ⁻	Plant Uptake	55%	Lowrance, 1992
TP	Mobilization	Increase	Osborne and Kovacic, 1993
DOP	Mobilization	Increase	Carlyle and Hill, 2001; Osborne and Kovacic, 1993; Vanek, 1991

2.4.1 Surface Runoff

Runoff traveling via surface runoff experience reductions in nutrients through deposition of sediment-bound nutrients (sedimentation) and exchange of dissolved nutrients with soil and leaf litter surfaces (adsorption) (Vought et al., 1994). Due to vegetation type and cover, N and P removals vary throughout the literature. As based upon grassed filter strip research, grassed watersheds may slightly reduce concentrations of sediment bound P or particulate TN, but generally do very little in

terms of nutrient transformation (Lowrance and Sheridan, 2005; Winston et al., 2012). Removal rates from a wooded buffer saw efficiencies as high as 86% and 84% for particulate bound organic-N and total particulate P, as well as removal of nitrate (79%) and ammonium (73%) (Peterjohn and Correll, 1984). Of the sites examined, most saw little change in dissolved P concentrations within the surface runoff fraction (Peterjohn and Correll, 1984; Lowrance and Sheridan, 2005).

2.4.2 Shallow Interflow

Shallow interflow is not a part of the water table, as flow is not considered saturated, but in instances of high laterally flowing water tables, it is hard to distinguish between shallow interflow and shallow groundwater. However, in these instances, removal mechanisms will be similar. For the purpose of this review, shallow lateral flow was treated as shallow interflow.

As interflow travels laterally through the soil horizon, it undergoes media filtration. Nutrients in water pass through root zones and are available for plant uptake (McDowell et al., 1992; Verchot et al., 1997). In most cases, the flow pathway is short and will not allow time for denitrification (Lindsey et al., 1998, Verchot et al., 1997). However, several studies have observed evidence of denitrification in shallow interflow when organic matter is present (Cooper, 1990; Cooper et al., 1995; Craig et al., 2008). When denitrification does not occur, the primary removal mechanism is plant uptake, but only during warm seasons (Verchot et al., 1997). Ultimately, 60% to 90% of nitrate and 33% TP was removed under optimal conditions. Unfortunately, conditions which are best for denitrification often see a release of previously bound P (Stevenson and Cole, 1999).

2.4.3 Groundwater

Nutrient concentrations in groundwater are extremely variable, depending on factors such as input concentration, soils, and depth of the aquifer. Removal mechanisms in groundwater primarily include denitrification and plant uptake in shallow

groundwater (Bohlke and Denver, 1995; Lowrance, 1992; Lowrance et al., 2000, Weil et al., 1990), and dilution by deep groundwater (Cey et al., 1999; Komor and Magner, 1996). Denitrification in shallow groundwater requires organic matter and low dissolved oxygen concentrations (Craig et al., 2008). Without these conditions, plant uptake becomes the primary mechanism, accounting for nitrate reductions up to 50% depending on root depth and vegetation type (Bohlke and Denver, 1995; Lowrance, 1992). Several studies have reported upwelling of nitrate-poor deep groundwater. Cey et al. (1999) reported a sharp decline in nitrate concentration upon entering the riparian zone where water and associated pollutants were able to quickly infiltrate downward (as opposed to laterally), and be replaced by deep nitrogen-poor groundwater. In very specific circumstances, studies have reported denitrification within the deep groundwater layers as a result of low DO concentrations and substrates able to provide an electron donor. Bohlke and Denver (1995) reported an 80% to 100% reduction in nitrogen from deep ground water discharging through a shallow anoxic zone below the stream bed. If conditions are anoxic, but no electron donor exists, ammonium will be the dominant form of nitrogen (McDowell et al., 1992).

2.4.4 Summary of Treatment Potential

The highest potential for P removal is in surface runoff and the aerobic zones of shallow interflow (Table 2-2). In contrast, N is removed best under anaerobic and reduced conditions within the subsurface pathways (Table 2-2). Ultimately, each pathway serves an important role in reducing nutrients, and thus must be present for removing both nitrogen and phosphorus. Since these mechanisms are present in undeveloped watersheds, they should also be present in SCMs intending to achieve predevelopment conditions.

2.5 Implications for SCM Design in the Piedmont, North Carolina

The importance of hydrograph separation in the context of striving for predevelopment hydrology in stormwater applications is two-fold. First, under

predevelopment conditions, surface runoff is not the main fraction of flow contribution to streams. Rather, subsurface flow contributions typically contribute a substantially larger fraction of stream flow. Second, each fraction of water undergoes multiple mechanisms of treatment important in removing a variety of pollutants. Therefore, under predeveloped conditions, the majority of the flow contribution to streams has undergone a high level of treatment, which reduces pollutant contributions to receiving waters.

To achieve true predevelopment hydrology in stormwater control design, an SCM must provide a hydrology that not only represents the predevelopment stream flow event contribution in terms of hydrograph volume, but also the treatment mechanisms associated with each pathway. Walsh et al. (2009) hint at this, suggesting that outflow from bioretention is not equivalent to a similar volume of surface runoff piped directly to receiving waters because of the additional treatment mechanisms present in the bioretention relative to surface runoff. This concept is especially important in soils with low hydraulic conductivity, where infiltration is small and, therefore, overall volume reduction provided by SCMs is minimal. Additionally, SCMs which are able to best mimic treatment mechanisms observed in all pathways will offer the best potential at maintaining ecosystem and public health. For example, a wet pond and a bioretention cell may release similar quantities of water from a developed site. However, the water released from the wetpond mostly undergoes sedimentation (GeoSyntec and WWE, 2008), whereas bioretention cells offer many different pollutant removal mechanisms prior to release (Hunt et al., 2012).

2.5.1 Evidence of Pathways in Bioretention Cells in North Carolina

The Piedmont of North Carolina is an optimal location for considering the pathways associated with predevelopment hydrology. Due to hydrologic soil group (HSG) C and D soils, as well as the shallow regolith, the NC Piedmont naturally exhibits three

distinct flow pathways contributing to the stream flow hydrograph – surface runoff, shallow interflow, and groundwater (Lowrance et al., 1997). Therefore, SCMs which are able to mimic these pathways may offer a tool to meet predevelopment hydrologic and water quality conditions.

Bioretention cells located within the NC Piedmont have shown evidence of flow pathways observed in undeveloped watersheds. Bioretention cells with internal water storage (IWS, Hunt et al., 2012) release water which 1) remains from a previous storm event (similar to predevelopment groundwater), 2) undergoes media filtration, but from the current event (similar to predevelopment shallow interflow), and, if a large enough rainfall event, 3) overflows into a vegetated swale (cognate to surface runoff). DeBusk et al. (2011) compared bioretention cell outflow hydrographs in the Piedmont to corresponding stream flow in pasture-based “target” watersheds. The results were nearly identical between the two, suggesting that bioretention outflow mimics shallow interflow (the tail end of the stream hydrograph) nearly perfectly.

Thus far, no study examines the age of the water exiting a bioretention cell to determine the cell’s ability to mimic the pre-event pathway. A preliminary investigation occurred on a bioretention cell with an IWS located in Knightdale, NC releasing water to Mango Creek (Luell et al., 2011). Samples were taken during Spring 2012 from the inflow and the outflow of one cell using ISCO 6712 automated samplers over the course of the storm hydrograph. The cumulative inflow sample and samples at selective points within the outflow hydrograph underwent analysis for deuterium concentration at Duke DEVIL Labs in Durham, NC. All four storms measured displayed outflow deuterium concentrations initially high relative to that of the inflow, but deuterium concentrations gradually decreased as more water was released from the cell (Figure 2-2). Stored water in the bioretention cell will increase

in deuterium concentration over time due to ET (Barnes and Allison, 1988; Friedman et al., 1964). Therefore, pre-event water will be enriched in deuterium as compared to the precipitation. These data, although preliminary, suggest that the bioretention cell initially releases pre-event water, and at least partially mimics the pre-event (groundwater surge) pathway observed in predevelopment conditions. Further data collection is essential in describing the hydrograph fraction of each pathway exhibited in bioretention cells.

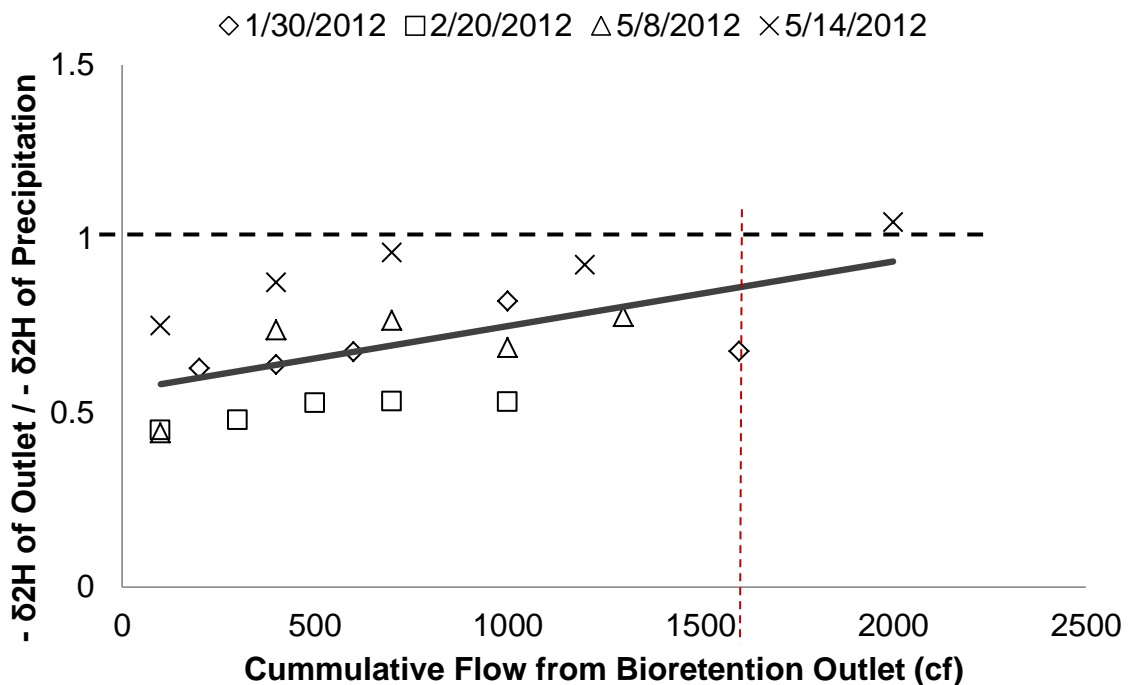


Figure 2-2 Summary of the deuterium isotope concentration ratio between outflow and inflow as compared to cumulative outflow. A ratio of 1 or higher suggests the water is predominantly event water. The internal water storage (IWS) is calculated as approximately 1600 cf of water (as indicated by vertical dotted line).

Ultimately, the connection must be made between the flow pathway capacity and water quality within SCMs. Bioretention cells constructed with internal water storage

(IWS), offering all three pre-development hydrology pathways, exhibit some of the highest degrees of N removal, both in lab-scale (Zinger et al., 2013) and field-scale monitoring (Brown and Hunt, 2011; Hurley and Forman, 2011; Passeport et al., 2009). However, further research is required to connect hydrograph fractions exiting from said systems to enhanced water quality. It is suspected that all predevelopment hydrologic pathways are necessary to truly optimize SCM design, particularly with the goal achieving predevelopment water quality conditions within a developed watershed.

2.5.2 Implications for SCM Design Beyond NC

Specific design aspects should be incorporated into SCMs based on this understanding of contributing pathways. To mimic groundwater surge, SCMs should collect and temporarily store runoff while providing media filtration and fluctuating redox conditions. Shallow interflow is mimicked by media filtration and exposure of runoff to plant roots. Conventional SCMs, such as swales or wetponds, already mimic treatment processes experienced by surface runoff.

Although bioretention is able to provide potential for each pathway, SCM design is not limited to such systems. For example, regenerative stormwater conveyance (RSC), which includes media underlying step-pool system, may also exhibit opportunities for all three pathways (Flores et al., 2012; Brown et al., 2010). Permeable pavement (Brattebo and Booth, 2003; Collins et al. 2008) design could be adjusted so that all three pathways of release can be realized. Further research and creative design is necessary to develop and analyze the potential of new SCM approaches which can truly mimic predevelopment hydrology.

2.6 Conclusions

Matching predevelopment hydrology on a developed site must include consideration of all flow pathways present in the undeveloped watershed (beyond just runoff, infiltration, and ET). This ensures predevelopment water quality associated with

each pathway is included in SCM design. Sustainable growth requires development which is able to truly mimic predeveloped conditions through specific definition of stormwater goals and sound and creative SCM design.

2.7 Acknowledgements

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3. Hydrologic Performance of Regenerative Stormwater Conveyance (RSC) in the North Carolina Coastal Plain

3.1 Abstract

Regenerative stormwater conveyance (RSC) is an open channel, sand-filtering system composed of a series of shallow aquatic pools, riffles and weirs, native vegetation, and underlying media beds. Surface runoff entering an RSC is conveyed as non-erosive surface flow or subsurface seepage through the media, and exits the system as surface flow, seepage out, exfiltration into parent soil, or evapotranspiration (ET). RSCs are expected to perform similar to other sand-media-based low impact development (LID) stormwater control measures (SCMs), but the hydrological and water quality efficiencies of RSC have not been sufficiently validated in a variety of hydrogeological conditions to date. An RSC was installed in Brunswick County, located in the Coastal Plain of North Carolina, receiving runoff from a 5.2 ha. Surface flow was reduced substantially through the RSC, with 86% of inflow converted to a shallow interflow-like seepage through the media, herein referred to as “seepage.” High groundwater levels resulted in small overall exfiltration rates, but increased evaporation rates due to extended ponding. The conversion of surface runoff to seepage out has significant implications for stormwater mitigation, releasing filtered water at slower rates than conventional conveyance channels, similar to undeveloped watersheds. The Brunswick RSC released similar fraction of seepage to that of shallow interflow observed in undeveloped watersheds.

3.2 Introduction

The conversion of undeveloped, pervious, land uses to urban and suburban, impervious, landscapes results in increased surface runoff during storm events. This excess stormwater runoff has been linked to stream degradation (Horner et al., 2003; Klein, 1979; Walsh et al., 2004), economic loss (Ajuzie and Altobello, 1997),

and public health concerns (Curriero et al., 2001; Gaffield et al., 2003). Stormwater mitigation efforts are active across the United States through the use of stormwater control measures (SCMs, also referred to as best management practices [BMPs]). Stormwater management initially focused on efficiently routing runoff directly to streams using pipe networks; then evolved to reducing erosive peak flows, and therefore downstream flooding, through SCM retention strategies; and then to improving water quality. Recently, stormwater management has focused on maintaining the pre-development (undeveloped land) hydrograph for a given watershed (Low Impact Development Center, 2007). In fact, the United States Government approved the Energy Independence and Security Act of 2007 requiring all federal land post-construction discharge conditions to match the pre-development hydrograph when disturbed land is greater than 465 m² (5,000 sf) (Energy Independence and Security Act, 2007). A given watershed hydrograph can include three possible flow pathways – 1) surface runoff, 2) shallow interflow, and 3) groundwater from previous rain events (pre-event water) (Brown et al., 1999; Kendell et al., 2001). Cizek and Hunt (2013) suggested that vegetated, filtration-based SCMs with water storage in the media include all three pathways and are therefore able to mimic pre-development hydrology.

Regenerative stormwater conveyance (RSC) is an emerging media-based SCM. This SCM is an open channel system consisting of a porous media bed with a series of riffle/weir step pools (Figure 3-1). Similar to other media-based SCMs, bed material with a high hydraulic conductivity is selected to promote infiltration. Unlike bioretention media (Hunt et al., 2012), RSC media includes 20% to 30% by volume shredded hardwood mulch to increase organic content and promote plant growth (Anne Arundel County Department of Public Works, 2012). The other 70 to 80% is composed of ASTM-C-33 specified sand, 0.5 mm to 1.0 mm in diameter. The riffle/pool geometry absorbs energy and retains water by promoting ponding and non-erosive flows. A native plant community may also increase both water quality

and hydrologic benefits through plant uptake, microbially-mediated pollutant transformation, and evapotranspiration.

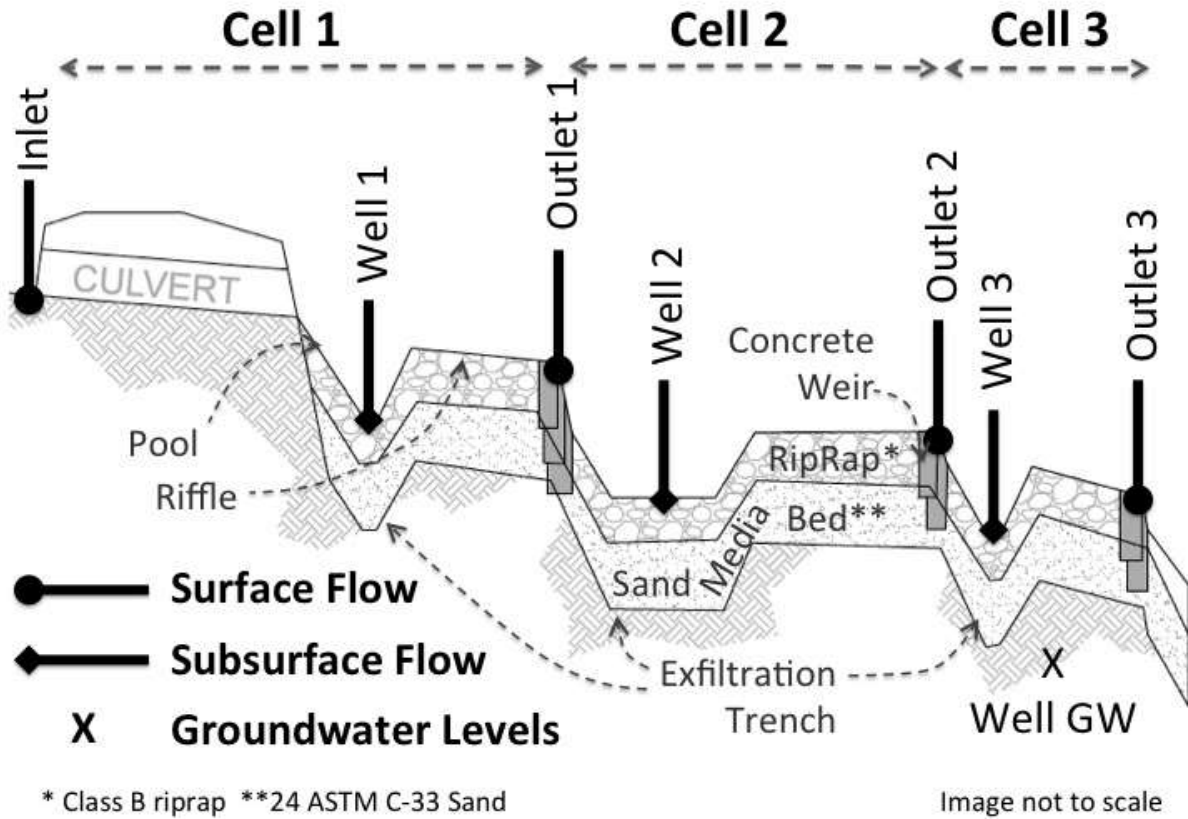


Figure 3-1 Brunswick County RSC cross-section with major design components and monitoring locations called out.

RSCs are designed to safely convey up to the 100-year average recurrence interval (ARI) rain event via non-erosive surface flows. During smaller rainfall events, water is expected to exit the system as seepage or infiltrated surface water percolating through the RSC sand media bed (cognate to shallow interflow, or water that travels

laterally through the upper soil horizons during or immediately following a precipitation event). Hydrologic TR-20 modeling of an RSC site receiving runoff from 7.2 ha of low-density residential development showed a 75% reduction in peak flow during the 25-year storm event (Brown et al., 2010). Surface flow velocities during that event were predicted to be a maximum, but non-erosive, 1 ms^{-1} with a max flow depth of 0.15 m over the outlet weir. Field-scale monitoring of another RSC receiving water from a 5.7-ha medium-density residential neighborhood had no less than a 50% reduction in peak flow for rainfall events less than 3.8 cm (Filoso, 2013). RSCs have many design characteristics that mimic pre-development hydrology, but field research supporting RSC performance is extremely limited. Further investigation is needed to determine the fate of water in this RSC, as well as the RSC's ability to mitigate stormwater runoff. Previous studies (non-peer reviewed) have focused on sites located in Anne Arundel County, Maryland (MD). Despite minimal field performance research, RSCs (also referred to as step pool stormwater conveyance [SPSC]) are credited SCMs in some jurisdictions for stormwater mitigation at tidal inlets, pipe outfalls, and eroded headwater streams (MD Department of the Environment, 2014).

The North Carolina Department of Transportation (NCDOT) is particularly interested in RSCs (referred to as biofiltration conveyances [BFCs] by NCDOT) as retrofit SCMs to repair eroding roadside gullies. An RSC installed for such a purpose in Brunswick County, NC, has been monitored for hydrology since 2010. Using the data collected from this site, this research aims to

- i. quantify the hydrological fate of runoff entering the RSC and
- ii. determine the ability of RSCs to provide hydrological mitigation of stormwater runoff

This work is critical in providing an initial benchmark for RSC system performance. No water quality monitoring was conducted during this investigation.

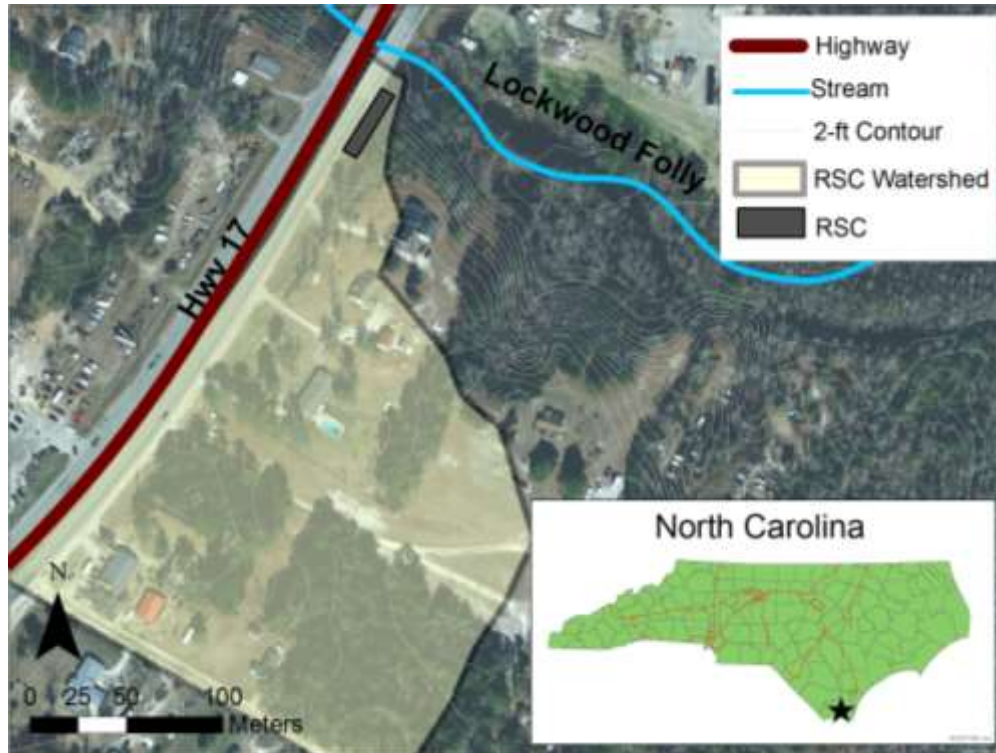
3.3 Methods

3.3.1 Site Description

The Brunswick County RSC is located along US Hwy 17 at the Royal Oak Bridge over the Lockwood Folly River near Supply, NC (34.02° N, 78.26° W). The watershed is 5.2 ha including 0.64 ha of impervious area, with Hwy 17 accounting for 0.23 ha (Table 3-1, Figure 3-2). The remaining land cover is composed of pine forest and brush. The site is dominated by Baymeade/Marvyn and Muckalee loam soils, both predominantly sandy Hydrologic Soil Group A soils (NRCS, 2007). Portions of the original swale in which the RSC was installed were heavily eroded, with a 1.5 m head cut at its downstream end. The 40-m long and 4.3-m wide RSC, constructed during summer 2012, begins at the end of a driveway culvert and is comprised of three pool/riffles with an average system slope of 4% (Figure 1). The sand media bed is 0.6 m deep separated by geotextile fabric from 0.46 m of Class A rip rap to stabilize the channel (Table 3-1). The geotextile layer in the second pool exhibited some evidence of clogging immediately after construction, which may have contributed to slower infiltration rates through this layer (discussed later). However, saturation of the sand-media below the fabric indicated that water would still eventually penetrate this layer. Precast concrete weirs (Figure 3-2b) were used in lieu of boulder weirs, as large boulders were not locally available. The entire SCM was covered in 50 mm of composted hardwood mulch and seeded with a stabilization mix. The RSC did not have any substantial vegetation during the monitoring period.

Table 3-1 Brunswick County RSC site description

	Cell 1	Cell 2	Cell 3
Contributing Watershed Area	5.1 ha		
Sand Media Depth	0.61 m		
Rip Rap Depth	0.46 m		
Ponding Depth	0.91 m		
Length	11.9 m	18.3 m	9.1 m
Width	4.3 m	4.3 m	4.3 m
Surface Area	50 m ²	78 m ²	39 m ²
Contributing Run On Area	395 m ²	368 m ²	184 m ²
Average Slope	2.5 %	3.7 %	6.5 %
Sand Media Available Storage	9.1 m ³	13 m ³	6.8 m ³
Rip Rap Available Storage	4.2 m ³	6.1 m ³	1.7 m ³
Pond Available Storage	20 m ³	56 m ³	55 m ³



(a)



(b)

Figure 3-2 (a) Brunswick County RSC and watershed location, and (b) Brunswick RSC one month after construction completion

3.3.2 Hydrologic Monitoring

Each pool/riffle series was monitored (Figure 3-1). Surface flow and exfiltration were measured using a series of weirs, wells, and pressure transducers.

Evapotranspiration was calculated using reference values measured at nearby weather stations, and seepage was calculated by completing the water balance.

Rainfall was measured by a tipping bucket rain gauge and a manual rain gauge located adjacent to the RSC. Groundwater levels in the RSC were monitored using a 3-m deep groundwater well located on the bank adjacent to the third pool.

Hydrologic monitoring occurred from October 2012 to March 2014.

3.3.2.1 Surface Water

Hobo™ U-20 pressure transducers were used to collect 2-min interval water depth measurements and temperature measurements at the inlet and outlet of each cell within the RSC. The inlet weir was located immediately upslope of the driveway culvert to avoid backwater submerging the weir (Figure 3-1). Each of the concrete riffle weirs forming the outlet of each cell were fitted with a compound weir composed of a 12.7-cm 90-deg V-notch lower section and a 0.9-m (3-ft) broad crested upper section. Flow for each 2-min interval was determined using the weir equation given the water level above the invert of the weir (Eq. 3-1).

$$Q = \begin{cases} 2.31h^{2.49} & h \leq 12.7 \\ 2.31h^{2.49} + 10L(h - 12.7)^{1.5} & h > 12.7 \end{cases} \quad \text{Eq. 3-1}$$

where Q is the flow rate(L/s), when pressure head is h cm

L is the length of the broad crested weir, 0.91 m

Depth measurements were converted to a flow rate and used to determine the peak flow and, when integrated, the overall volume from the RSC for each measured rainfall event. Peak flow and volume were compared for each RSC weir to calculate RSC flow and volume reductions.

In addition to surface flows entering the RSC via the inlet weir, runoff from the adjacent highway was expected to enter each cell as overland flow. This surface volume contribution is calculated using the SCS Curve Number Method (SCS, 1985). Curve numbers (CN) for the roadway and brushy shoulder were estimated as 98 and 48, respectively. Contributing run-on areas for each cell are described in Table 1. Precipitation falling directly on each cell was accounted for as well.

3.3.2.2 Exfiltration

The media bed was designed to facilitate exfiltration into the parent soil, and eventually into the groundwater, similar to the function of bioretention media (Brown, 2010). An exfiltration trench, where the bottom of the media bed followed the surface pool contours, was located within each cell enabling the estimation of exfiltration rates (Figure 3-1). As with the surface measurements, Hobo™ U-20 pressure transducers within wells were used to measure the height of water within the media bed in each pool. Water stored below the top of the exfiltration trench could only leave the RSC via exfiltration into the parent soil. From that point the drawdown of the water level and associated volume reductions were solely attributed to exfiltration; volume changes were used to calculate the instantaneous exfiltration rate at 2-min intervals. A regression analysis was used to determine the relationship between the volume of water exfiltrated and the stage of the water within the media. Exfiltration was then back calculated over the entire storm event for water stages exceeding the height of the exfiltration trench.

3.3.2.3 Evapotranspiration

Despite the RSC being seeded with stabilization grass mix and mulched, vegetation did not establish during the 16-month monitoring period, due to seeds and mulch being through and into the riprap layer, as well as extended ponding flooding the seeds. As such, evaporation rates were estimated *only* when water was ponded on the RSC. Pan evaporation values from KSUT-Brunswick Co Airport in Southport, NC (33.93 N, 78.07 W), located 25.75 km from the RSC, were multiplied by a PAN

coefficient of 0.9 (estimated from Allen and Pruitt, 1991), and used to estimate evaporation. Extended ponding allowed for continuous evaporation between rainfall events, which, if considered, would overestimate evaporative losses associated with a single event. Therefore, evaporative losses specific to a rainfall event were only considered when water stored within the RSC increased due to incoming runoff until it returned to its pre-rainfall amount (i.e. when final storage was equal to initial storage).

3.3.2.4 Seepage

Water levels monitored within the sampling wells were originally intended to be used for calculating seepage, or horizontal subsurface flow from one cell to another, within the RSC media bed. However, unanticipated high groundwater levels were observed in the on-site groundwater well, resulting in long-term ponding within the pools of each cell. These persistently high water levels within the media rendered any seepage calculations impossible. Instead, seepage was calculated using all the previously determined inflow and outflows. For each cell, the following water balance was calculated (Eq. 3-2).

$$\Delta Storage = V_{surf,in} + V_{seep,in} + V_{RO} - V_{surf,out} - V_{seep,out} - E - Ex \quad \text{Eq. 3-2}$$

where $\Delta Storage$ is the change in storage

V_{surf} is the surface volume into and out of the cell

V_{seep} is the seepage volume into and out of the cell

V_{RO} is the precipitation and run-on volume entering the cell through overland flow, as opposed to through the inlet weir

E is the calculated evaporation

Ex is the calculated exfiltration

RSC storage for each cell was determined based on stage-storage calculations. As the system was frequently wet, specific yield for the sand media and rip rap was estimated as 30% and 25%, respectively (Stephens et al., 1998).

3.3.2.5 Pre-development Conditions

Pre-development runoff conditions were compared to RSC outflow to determine the extent to which the RSC was able to mimic pre-development hydrology during the monitoring period. Pre-development runoff volumes and flows of each storm event were calculated using the SCS Curve Number Method (SCS, 1985) and the Rational Method (ASCE, 1996). Vegetation in this 5.2-ha watershed is primarily woody. Conservative pre-development conditions were modeled, with an SCS curve number of 35 and a rational runoff coefficient of 0.15. Given the calculated runoff volume and peak flow, a step-function described in Eq. 3-3, (Malcom, 1989), was used to estimate the center-weighted pre-development hydrograph for each storm event.

$$q_i = \begin{cases} \frac{Q_p}{2} \left[1 - \cos\left(\frac{\pi t_i}{T_p}\right) \right] & \text{for } t_i \leq 1.25T_p \\ 4.34Q_p \exp\left(-1.30 \frac{t_i}{T_p}\right) & \text{for } t_i > 1.25T_p \end{cases} \quad \text{Eq. 3-3}$$

where q_i is the respective flow rate for time t_i m^3/s

Q_p is peak design flow rate in m^3/s

T_p is the time to Q_p in seconds, calculated by $T_p = \frac{V}{1.39Q_p}$

V is the total runoff volume in m^3

3.4 Results

A total of 27 inflow-producing events were monitored from October 2012 to March 2014. Inflow producing precipitation depths ranged between 5.8 mm and 74.3 mm (Table 3-2). The SCS curve number was back-calculated and plotted for each event to verify that inflow data was reasonable given known watershed characteristics

(Figure 3-3). Admittedly for storm depths the SCS did not intend curve numbers to be used, the data did show a trend asymptotically approaching a watershed curve number in the low 40's (Hawkins, 1993, Mullem et al., 2000). Given the aforementioned land has 0.64 ha impervious area (CN of 98) and 4.56 ha of brush/forest cover (CN of 35), the estimated composite curve number for the watershed is 43, which corresponds well with inflows observed at the RSC.

Of 27 events, only *two* events resulted in surface outflow from the RSC. The first, 1.4 m³ of inflow occurring on October 8, 2012, followed within 24 hours of a previous event, and produced < 1 m³ of outflow. The second outflow-producing event resulted from 22 m³ of inflow from Tropical Storm Andrea (June 6-7, 2013). Additionally, only two events resulted in surface outflow exiting Cell 1, one of which was Tropical Storm Andrea. The other, occurring on October 7, 2012, resulted from only 30 mm of rainfall, an amount that never again produced surface outflow from Cell 1. There was initially a problem with alternative subsurface flow pathways around the concrete weirs, hence short-circuiting around Outlet 1 (Figure 3-1), where the concrete weir tied into the parent soil. This was repaired in late October 2012 using sand bags and riprap, which likely prevented high volumes of flow from passing this way, but may not have altogether eliminated the alternative pathway around the weir. Groundwater levels monitored in the neighboring (control) well were higher than the base of the RSC, indicating groundwater was indeed present in RSC media, interacting with the stormwater runoff.

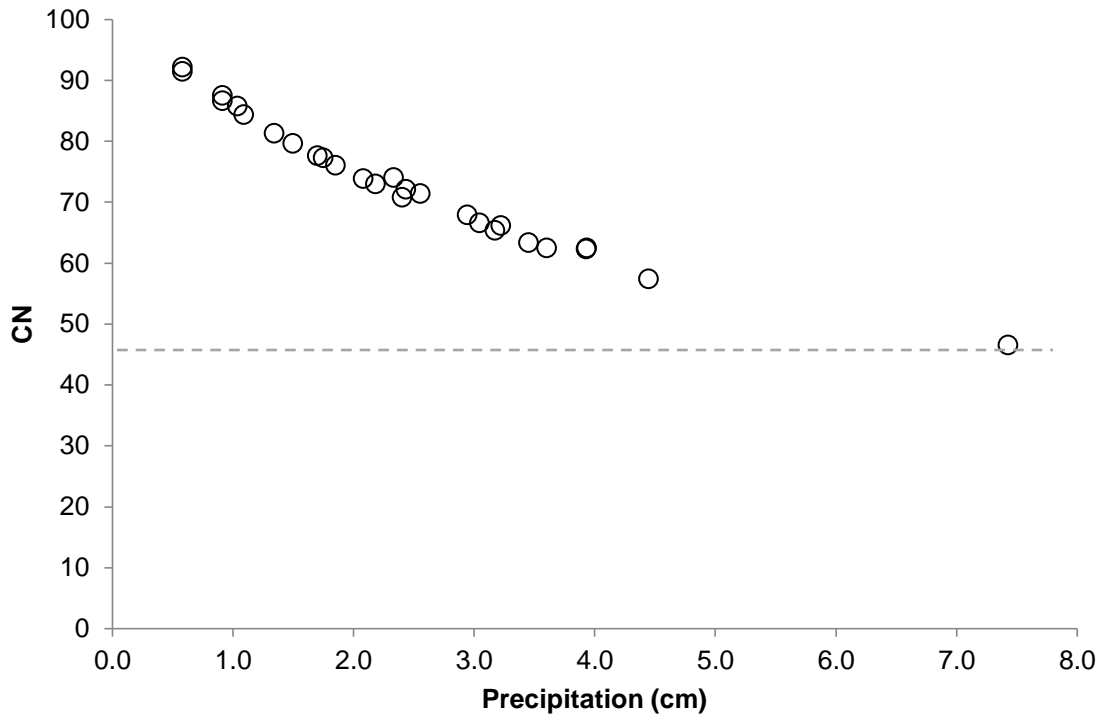


Figure 3-3 Relationship between watershed runoff contributions to RSC and back-calculated curve numbers (CN).

Table 3-2 Overall water balance in the Brunswick RSC from October 2012 to March 2013, including surface inflow/outflow, exfiltration, evaporation, and run on.

		Cell 1						Cell 2						Cell 3							
		IN (mm)		OUT (mm)				IN (mm)			OUT (mm)			IN (mm)			OUT (mm)				
<i>Date</i>	<i>Precip (mm)</i>	<i>Sur</i>	<i>Run On</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>	<i>Sur</i>	<i>Run On</i>	<i>Seep</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>	<i>Sur</i>	<i>Run On</i>	<i>Seep</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>
10/7/12	30	0.12	0.03	0.00	0.15	0.00	0.00	0.00	0.05	0.15	0.00	0.20	0.00	0.00	0.00	0.02	0.20	0.00	0.22	0.00	0.00
10/8/12	18	0.03	0.02	0.00	0.04	0.00	0.00	0.00	0.03	0.04	0.00	0.07	0.00	0.00	0.00	0.01	0.07	0.00	0.08	0.00	0.00
11/18/12	36	0.05	0.04	0.00	0.09	0.00	0.00	0.00	0.06	0.09	0.00	0.15	0.00	0.00	0.00	0.03	0.15	0.00	0.18	0.00	0.00
12/12/12	22	0.02	0.02	0.00	0.04	0.00	0.00	0.00	0.03	0.04	0.00	0.06	0.01	0.00	0.00	0.02	0.06	0.00	0.07	0.00	0.00
12/25/12	31	0.07	0.03	0.00	0.10	0.00	0.00	0.00	0.05	0.10	0.00	0.14	0.01	0.00	0.00	0.02	0.14	0.00	0.16	0.00	0.00
3/19/13	14	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.00	0.01	0.02	0.00	0.03	0.00	0.00
3/24/13	32	0.05	0.03	0.00	0.08	0.01	0.00	0.00	0.05	0.08	0.00	0.11	0.02	0.00	0.00	0.02	0.11	0.00	0.13	0.00	0.00
4/4/13	21	0.01	0.02	0.00	0.03	0.00	0.00	0.00	0.03	0.03	0.00	0.06	0.00	0.00	0.00	0.02	0.06	0.00	0.08	0.00	0.00
4/19/13	24	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.04	0.02	0.00	0.03	0.02	0.00	0.00	0.02	0.03	0.00	0.04	0.01	0.00
5/20/13	19	0.01	0.02	0.00	0.01	0.01	0.00	0.00	0.03	0.01	0.00	0.02	0.02	0.00	0.00	0.01	0.02	0.00	0.03	0.00	0.00
5/23/13	9	0.01	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
6/6/13	74	0.43	0.18	0.00	0.59	0.01	0.00	0.00	0.22	0.59	0.01	0.79	0.01	0.00	0.01	0.09	0.79	0.02	0.87	0.01	0.00
6/29/13	15	0.01	0.01	0.00	0.02	0.00	0.00	0.00	0.02	0.02	0.00	0.04	0.00	0.00	0.00	0.01	0.04	0.00	0.05	0.00	0.00
6/30/13	6	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.03	0.03	0.00	0.06	0.00	0.00	0.00	0.02	0.06	0.00	0.08	0.00	0.00
6/30/13	10	0.01	0.02	0.00	0.03	0.01	0.00	0.00	0.03	0.03	0.00	0.04	0.01	0.00	0.00	0.02	0.04	0.00	0.06	0.00	0.00
7/2/13	9	0.01	0.03	0.00	0.03	0.01	0.00	0.00	0.03	0.03	0.00	0.04	0.02	0.00	0.00	0.02	0.04	0.00	0.06	0.00	0.00
7/11/13	39	0.31	0.05	0.00	0.36	0.00	0.00	0.00	0.07	0.36	0.00	0.43	0.00	0.00	0.00	0.03	0.43	0.00	0.46	0.00	0.00
7/13/13	26	0.16	0.02	0.00	0.17	0.01	0.00	0.00	0.04	0.17	0.00	0.21	0.01	0.00	0.00	0.02	0.21	0.00	0.22	0.01	0.00
7/29/13	24	0.13	0.02	0.00	0.11	0.04	0.00	0.00	0.04	0.11	0.00	0.08	0.06	0.00	0.00	0.02	0.08	0.00	0.07	0.03	0.00
8/14/13	35	0.04	0.04	0.00	0.08	0.00	0.00	0.00	0.06	0.08	0.00	0.14	0.00	0.00	0.00	0.03	0.14	0.00	0.17	0.00	0.00
8/16/13	39	0.28	0.05	0.00	0.33	0.00	0.00	0.00	0.07	0.33	0.00	0.40	0.00	0.00	0.00	0.03	0.40	0.00	0.43	0.00	0.00

Table 3-2 (continued)

		Cell 1						Cell 2						Cell 3							
		IN (mm)		OUT (mm)				IN (mm)			OUT (mm)			IN (mm)			OUT (mm)				
<i>Date</i>	<i>Precip (mm)</i>	<i>Sur</i>	<i>Run On</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>	<i>Sur</i>	<i>Run On</i>	<i>Seep</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>	<i>Sur</i>	<i>Run On</i>	<i>Seep</i>	<i>Sur</i>	<i>Seep</i>	<i>E</i>	<i>Exfil</i>
8/23/13	11	0.01	0.01	0.00	0.02	0.00	0.00	0.00	0.02	0.02	0.00	0.04	0.00	0.00	0.00	0.01	0.04	0.00	0.04	0.00	0.00
9/22/13	23	0.23	0.02	0.00	0.26	0.00	0.00	0.00	0.04	0.26	0.00	0.29	0.00	0.00	0.00	0.02	0.29	0.00	0.31	0.00	0.00
11/26/13	32	0.16	0.03	0.00	0.07	0.00	0.12	0.00	0.05	0.07	0.00	0.12	0.00	0.00	0.00	0.02	0.12	0.00	0.12	0.00	0.02
12/14/13	17	0.01	0.02	0.00	0.03	0.00	0.00	0.00	0.03	0.03	0.00	0.05	0.00	0.00	0.00	0.01	0.05	0.00	0.06	0.00	0.00
2/11/14	45	0.06	0.05	0.00	0.11	0.01	0.00	0.00	0.07	0.11	0.00	0.17	0.01	0.00	0.00	0.04	0.17	0.00	0.21	0.00	0.00
2/15/14	6	0.02	0.01	0.00	0.03	0.00	0.00	0.00	0.01	0.03	0.00	0.03	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.00	0.00
Total	665	2.26	0.85	0.01	2.84	0.14	0.12	0.01	1.21	2.84	0.01	3.79	0.25	0.00	0.01	0.59	3.79	0.03	4.26	0.08	0.02

3.4.1 Water Balance

Because the watershed was sandy, the majority of runoff entering the system (53%) did so as run-on from adjacent Hwy 17, as opposed to through the driveway culvert (Table 3-2). As described earlier, this part of the watershed contained the impermeable surface of Hwy 17 followed by a steeply sloped shoulder leading into the RSC. Therefore, it is reasonable that run-on contributed a large amount of additional inflow volume to each cell. The cells effectively converted most (86%) surface flows to subsurface seepage through the media, and eventually seepage from the RSC.

Many exchanges between surface flows and subsurface flows occur throughout the RSC. The “conversion” of a drop of runoff from surface flow to subsurface flow in Cell 1 does not mean that that same drop will not re-emerge as surface flow in Cell 2, as observed by water seeping between concrete weirs during Tropical Storm Andrea (June 6-7, 2013). During Andrea, measured surface flow volume was reduced to 0.11 m³ in Cell 1; then gradually increased to a surface flow volume of 1.25 m³ in subsequent Cells 2 and 3. These exchanges have an important implication for effluent water quality: in this case, surface flow almost always underwent some level of media treatment via subsurface flow prior to leaving the RSC (Peterjohn and Correll, 1984; Cooper, 1990; Lowrance et al., 2000).

In addition to surface/subsurface exchanges for the stormwater entering the RSC, a fluctuating groundwater table resulted in interchanges between stormwater and groundwater. The seasonally high water table (SHWT) was estimated to be 2.4 m below the bottom of Cell 2 prior to construction of the RSC from historical records. Construction was completed in June 2012. When monitoring began in October 2012, permanent ponding was observed within the RSC sand media, with corresponding groundwater levels in the adjacent monitoring wells. Cell 2 had ponded water in its pool from October 2012 through June 2013. Ponding in this cell was again observed

in February 2014 and through the remainder of the monitoring period. Increases in groundwater levels have been associated with stream restoration projects (Hammersmark et al., 2008) and beneath bioretention cells due to mounding (Endreny and Collins, 2009; Machusick et al., 2011), although the mounding only occurred for short durations after the precipitation event. Water was periodically ponded in Cells 1 and 3, but for shorter durations than Cell 2. The continuously ponded water in Cell 2 resulted in wetland-like conditions, leading to the emergence of a thriving *Typha* (cattail) community (Figure 3-4). Extended ponding enabled 10% of the overall volume to be evaporated. In November 2013, water levels within the media of Cell 1 drained below top of the exfiltration trench (Figure 3-1), allowing exfiltration rates to be calculated. Regression analysis found an irregular relationship between water level in the media and exfiltration loss normalized by area (Figure 3-5). Initial high rate of exfiltration may be due to the parent soil being unsaturated. As more water is present in the media around the parent soil, the exfiltration rate moves towards the saturated exfiltration rate (K_{SAT}), represented by the second line. It is possible that the steep curve of the third line includes both lateral flow and exfiltration, suggesting that the top of the exfiltration trench is not precisely at 0.63 m, but slightly lower. As no survey was taken prior to filling the media bed, the top of the exfiltration trench was considered to be 0.57 m from this point further, as indicated in Eq. 3-4.

$$r_{vol} = \begin{cases} 208.9x - 51.3 & 0.24 < x < 0.26 \\ 11.7x + 0.075 & 0.26 < x < 0.63 \end{cases} \quad \text{Eq. 3-4}$$

where r_{vol} is the change in storage (L/h/m²)

d is the stage of water in exfiltration trench above the parent soil (m)

Exfiltration was expected to occur when groundwater levels were below the top of the trench at the beginning of the storm. When it occurred, exfiltration accounted for up to 53% of water loss on a storm-by-storm basis, ultimately comprising 3% of the total runoff loss during the entire monitoring period (Table 3-2).

As designed, the majority (86% in this case) of the stormwater entering the RSC left the system as seepage from both the sand and rip rap media layers (Table 3-2). This may have important implications for water quality mitigation, as any seepage out has been subject to some level of media treatment through the RSC sand layer, although the distance water has traveled through this layer likely varies.



Figure 3-4 Typha community in Cell 2, July 2014

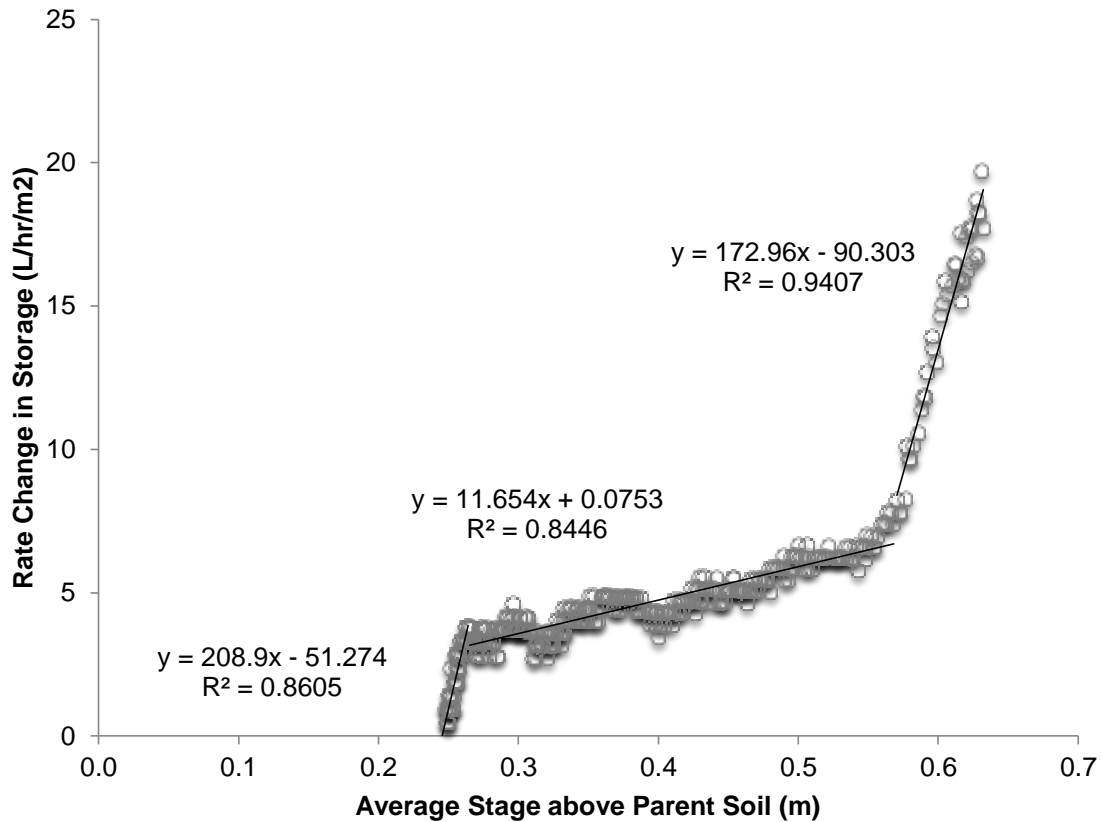


Figure 3-5 Relationship between exfiltration rates per area and the average stage above parent soil.

3.4.2 Volume and Peak Flow Mitigation

Surface flow volumes were reduced between 94% and 100% on a storm-by-storm basis. When surface outflow occurred, peak flow discharge rates decreased between 90% and 96%. Flow was observed being well distributed across the 4.6-m wide, 0.3-m deep channel, and overtopped the v-notch weir at a maximum non-erosive velocity of 0.3 m/s. This same flow spread out over the entire concrete weir in the absence of monitoring equipment would result in a outflow velocity of 0.6 cm/s.

Because many jurisdictions are adopting pre-development hydrograph-based stormwater goals (Low Impact Development Center, 2007), the modeled pre- and measured post-development hydrographs were compared. The pre-development watershed was sandy and woody so that a runoff-producing event would need to exceed 94 mm of rainfall, just less than the 1-yr, 24-hr rainfall event for the area. As no event this large occurred during the monitoring period, no runoff would theoretically have been yielded under pre-development conditions for the monitored storm events. The post-development inflow hydrograph was represented by the inflow hydrograph recorded at the inlet of the RSC, although this is a conservative representation as it does not consider the contribution of direct run-on from Hwy 17. The post-development effluent hydrograph from the RSC is represented by the recorded RSC surface outflow from the outlet of Cell 3. Because the SCS Curve Number Method used to estimate the pre-development conditions only accounts for direct runoff contributions to the storm hydrograph (SCS, 1985; NRSC, 1986), only surface outflow from the RSC was considered in the post-development hydrograph. The RSC did mimic the pre-development hydrograph for 25 of the 27 runoff producing events (or 94% of the time). However, Tropical Storm Andrea on June 6-7, 2013 (74.4 mm) produced 1.25 m³ of surface outflow from the RSC, where the pre-development would have yielded zero outflow (Figure 3-6). So, despite the superior surface flow reductions observed, performance of the Brunswick County RSC did not achieve pre-development hydrologic conditions all of the time, namely for extreme weather events such as a Tropical Storm.

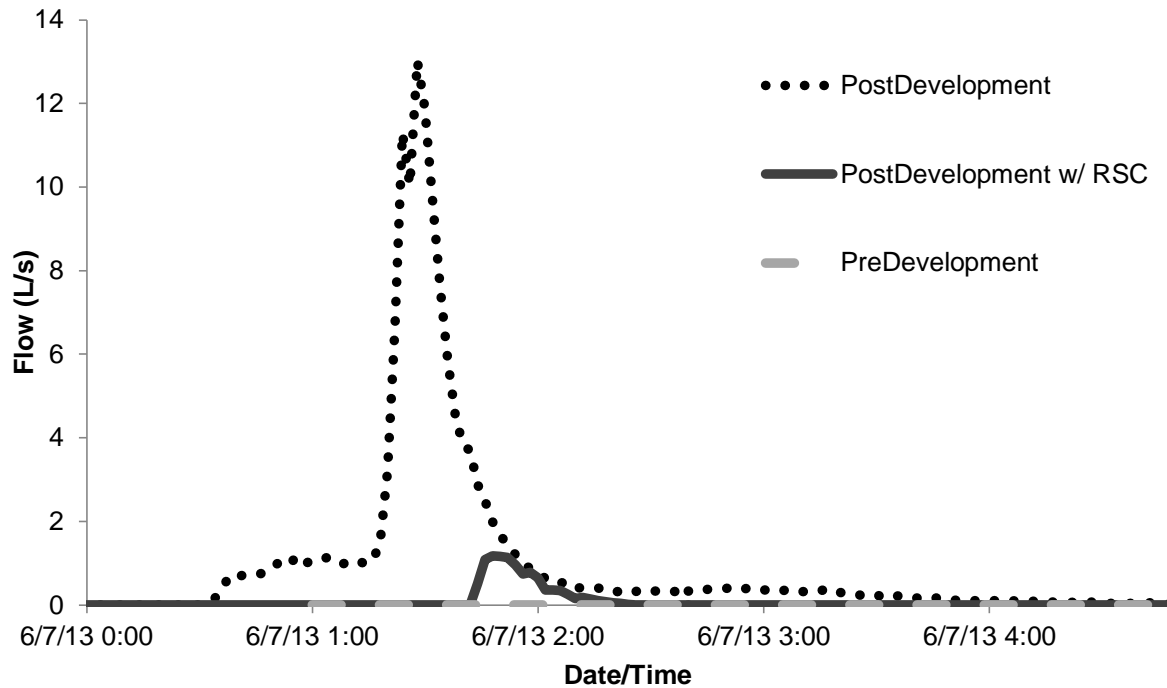


Figure 3-6 Pre-development (modeled) and post-development (measured) hydrographs for June 6-7 rainfall event, 74.3 mm

3.5 Discussion

The Brunswick County RSC mitigated surface runoff flows by converting inflow to predominantly subsurface seepage (cognate to shallow interflow). Eighty-four percent of the runoff entering the RSC exited as seepage. Previous research on undeveloped watersheds suggests that surface runoff only comprises a relatively small fraction (a median of 20% on a storm-by-storm basis) of the overall stream hydrograph (Brown et al., 1999). The fraction of surface runoff leaving this RSC was even smaller (2%). Many studies have found that storm hydrographs from undeveloped watersheds are comprised of 10% to 35% event water (surface runoff and shallow interflow) and 65% to 90% pre-event water (groundwater) (Brown et al., 1999; Soulsby, 1995, Wenninger et al., 2004; Williams and Pinder, 1990). As groundwater was present in the media bed for 90% of the monitoring period, it is

likely that a large portion of the seepage was comprised of pre-event water, though this was not measured. A temperature mass balance, as described by Nath (1996) and in Eq. 3-5, was used to estimate the total amount of water leaving the system as seepage (including stormwater and groundwater) herein.

$$\frac{dT}{dt} = \frac{Q_i T_i}{V} - \frac{Q_e T_e}{V} + \frac{\phi_{net}}{\rho_w c_{pw} d} - \frac{T}{V} \left(\frac{dV}{dt} \right) \quad \text{Eq. 3-5}$$

where T is the temperature ($^{\circ}\text{C}$) of the water in the cell, the inflow (i) and the outflow (e)

Q is the flow rate (m^3s^{-1}) of the inflow (i) and the outflow (e)

V is the total volume of water stored in the cell (m^3)

ρ_w is the density of water (kg m^{-3})

c_{pw} is the heat capacity of water ($\text{kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$)

d is the depth of the ponded water (m)

ϕ_{net} is the interfacial heat transfer due to various processes occurring at the water surface ($\text{kJ m}^{-2} \text{ s}^{-1}$)

Heat transfer processes considered for ϕ_{net} included net short-wave radiation penetrating the water surface, net atmospheric long-wave radiation, long-wave water surface radiation, evaporative heat transfer, and conductive heat transfer. Detailed equations are described by Nath (1996). Total seepage is *estimated* here, as a true calculation of the water balance requires more extensive groundwater monitoring. If the seepage calculated through Eq. 3-5 is considered to represent total seepage leaving the RSC (Seep_{tot}), and the *runoff* leaving as seepage is calculated using Eq. 2 ($V_{seep.out}$, renamed Seep_{RO} for the purpose of this discussion), then groundwater leaving the RSC as seepage (Seep_{GW}) would be described by Eq. 3-6.

$$\text{Seep}_{tot} = \text{Seep}_{RO} + \text{Seep}_{GW} \quad \text{Eq. 3-6}$$

Using this approach, the median fraction of pre-event water (or groundwater) leaving the system per storm is 95%, similar to that measured in undeveloped watersheds on the Coastal Plain (Williams and Pinder, 1990). This finding is important as it appears the Brunswick RSC is very close to mimicking the pre-development surface *and* subsurface flow pathways.

Several important design implications arise from this study. The exfiltration trenches used to measure exfiltration rates in the media also promoted exfiltration that would not have otherwise occurred. When groundwater levels were below the entire exfiltration trench, exfiltration accounted for up to 53% of a storm event's runoff due to the parent soil's high hydraulic conductivity (5 to 45 mm/hr). Even in non-sandy parent soils where exfiltration rates may not be high, the exfiltration trenches should enhance volume reduction. Brown and Hunt (2011) also showed an increase in exfiltration volume and rates from bioretention cells when water is retained in the media via internal water storage (IWS), further supporting the volume reduction benefits of water detention design, such as exfiltration trenches, in RSC design.

3.6 Conclusion

Regenerative stormwater conveyance effectively converts surface flow to a cognate of shallow interflow, with the potential to achieve further volume reductions via evapotranspiration and exfiltration. In this case study, this RSC was able to provide hydrologic stormwater mitigation through surface volume reduction, peak flow mitigation, and non-erosive flow velocities. Furthermore, this RSC demonstrated promising design characteristics, including volume reduction and opportunities for multiple hydrograph flow pathways, to help achieve pre-development hydrologic conditions; further research should be undertaken into this SCM's ability to mitigate stormwater runoff. Overall, RSCs appear to be an effective approach to managing stormwater runoff, and may eventually be considered a viable and valuable tool in the SCM toolbox.

3.7 Acknowledgements

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4. Water Quality and Hydrologic Performance of a Regenerative Stormwater Conveyance (RSC) in the Piedmont, North Carolina

4.1 Abstract

Regenerative stormwater conveyance (RSC) is an emerging vegetated, media-based approach to stormwater management. An RSC in the North Carolina Piedmont (USA), was monitored for hydrologic and water quality performance. Hydrologically, the RSC reduced volume and peak flow by 84% and 80%, respectively, while mimicking both predevelopment hydrograph shape and hydrologic flow pathways. The RSC was also able to reduce TSS, TP, and TN in surface flow by 72%, 28%, and 30%, respectively, likely due to physical treatment processes. The potential exists for further nutrient reduction if vegetated, wetland-like conditions are present. RSC outflow matches modeled predevelopment hydrograph shape and pathway components, including both pre-event and event water, as determined by deuterium concentrations. Optimal storm mitigation performance is expected when RSCs include a minimum of three pool/riffle cells, established vegetation, and exfiltration trenches to promote exfiltration into parent soils and extended subsurface ponding.

4.2 Introduction

The conversion of undeveloped, pervious, land uses to urban and suburban, impervious, land uses results in increased surface runoff rates, volumes, and borne pollutants. This excess stormwater runoff has been linked to stream degradation (Horner et al., 2003; Klein, 1979; Walsh et al., 2004), economic loss (Ajuzie and Altobello, 1997), and public health concerns (Curriero et al., 2001; Gaffield et al., 2003). As a result, stormwater mitigation efforts are increasing across the United States and elsewhere through the use of stormwater control measures (SCMs, also

referred to as best management practices, BMPs). Since the 1980s, stormwater mitigation has evolved to reducing erosive peak flows through SCM retention strategies, and then to improving water quality. Most recently, stormwater mitigation in many regions of the United States has focused on maintaining the predevelopment (undeveloped) hydrograph for a given watershed (Low Impact Development Center, 2007). It is likely that stormwater mitigation across the United States will move towards the pre-development hydrograph-based stormwater goals, particularly as the United States Federal Government adopted the Energy Security and Independence Act of 2007 requiring all federal land post-construction discharge conditions to match the pre-development hydrograph when disturbed land exceeds 465 m² (5,000 sf) (Energy Independence and Security Act, 2007). Studies in undisturbed watersheds have shown storm hydrographs to include three possible flow pathways: 1) surface runoff, 2) shallow interflow, and 3) groundwater from previous rain events (pre-event water) (Brown et al., 1999; Kendell et al., 2001). Cizek and Hunt (2013) suggested that vegetated, filtration SCMs with water storage in the media are able to simulate all three pathways when a watershed is developed, and are therefore able to at least partially match predevelopment hydrology.

Regenerative stormwater conveyance (RSC) is a relatively new vegetated, media-based approach to stormwater management. RSCs are open channel systems consisting of a porous media bed with a series of riffle/weir step pools (Figure 4-1). Similar to other media-based SCMs, the bed material has a high hydrologic conductivity to promote infiltration into the RSC media. Unlike recommended bioretention media (Hunt et al., 2012), RSC media includes 20% to 30% shredded hardwood mulch to serve as a carbon source for nutrient transformations (Anne Arundel County Department of Public Works, 2012). The riffle/pool geometry absorbs energy and retains water by promoting ponding water in shallow pools and slowing water to non-erosive flow velocities. A native plant community may also

increase both water quality and hydrologic benefits through plant uptake and evapotranspiration.

RSCs are designed to safely convey the 100-year average recurrence interval (ARI) rainfall event via non-erosive surface flows. During smaller rainfall events, water is expected to exit the system as seepage (cognate to shallow interflow). Hydrologic TR-20 modeling of an RSC site receiving runoff from 7.2-ha of low-density residential development in Anne Arundel County, Maryland showed a 75% reduction in peak flow during the 25-year storm event (Brown et al., 2010). Surface flow velocities during that event were predicted to be a maximum, but non-erosive, 1 ms^{-1} with the max flow depth of 0.15 m over the outlet weir. As observed by field scale monitoring, another RSC receiving water from a 5.7-ha medium-density residential neighborhood in Maryland provided up to 50% reduction in peak flow for rainfall events less than 38 mm (Filoso, 2013).

Documented water quality performance in RSCs is limited to non-peer-reviewed reports. Filoso (2013) compared RSC performance to a control headwater stream in a neighboring watershed. TSS concentrations exiting the RSC were 60% less than the control stream, with median outflow concentrations of 20 mg/L. Total phosphate removal mirrored TSS removal, where there was no overall difference in Nitrate-N (NO_3), Ammonium (TAN), total dissolved nitrogen (TDN), or total nitrogen (TN) outflow concentrations between the control stream and the RSC. Browning (2008) monitored a flat, wet RSC in Maryland (MD). She reported 0% to 50% TSS removal in the RSC, but with similar median outflow concentrations found by Filoso et al. (2013). In contrast to Filoso et al. (2013), this flat, wet RSC consistently reduced NO_3 and TAN by 20% to 40%, respectively, suggesting that a wetter system may provide more opportunities for nitrogen biotransformation (i.e. nitrification and denitrification).

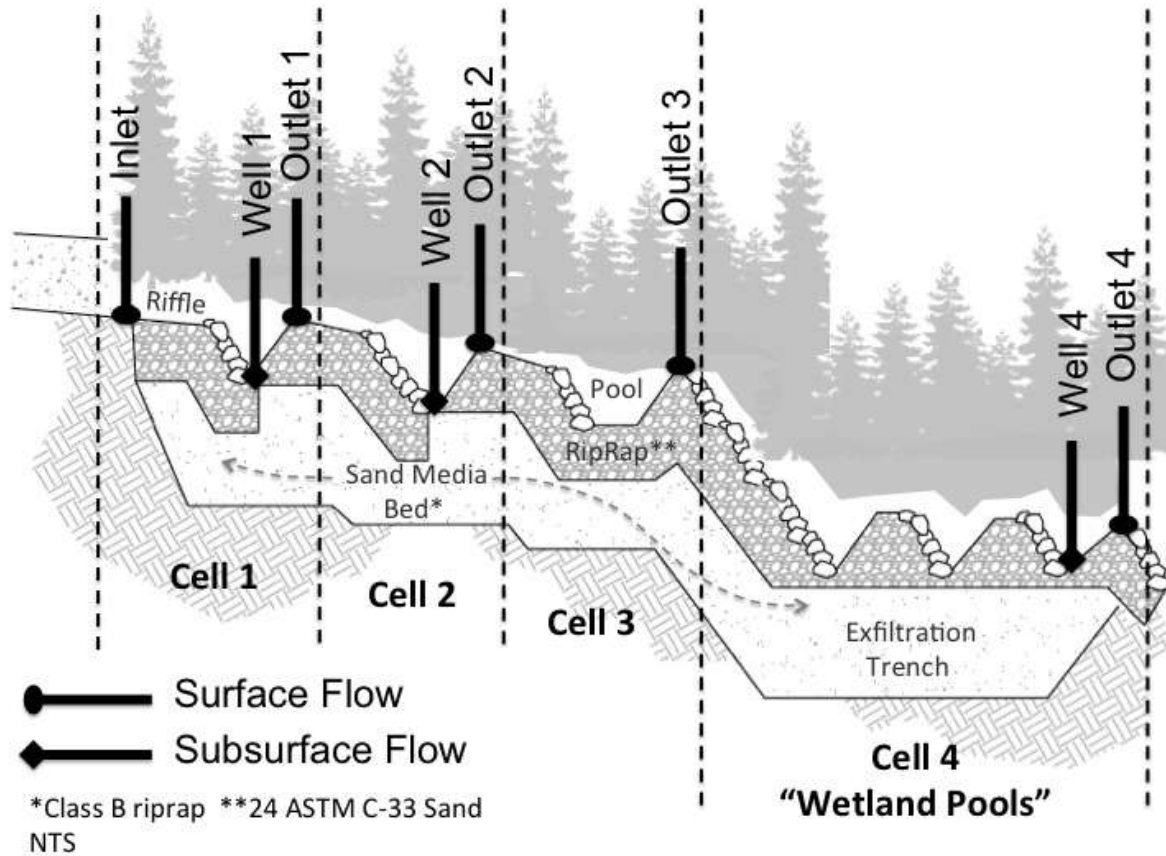


Figure 4-1 Alamance RSC profile with important design aspects and monitoring points labeled

Despite the minimal research on field performance, RSCs (referred to as step pool stormwater conveyance [SPSC] by MD DOE) are a choice tool in MD and Washington, D.C., for stormwater mitigation at tidal inlets, pipe outfalls, and eroded headwater streams (MD Department of the Environment, 2014; Ralph Spangolo, US EPA, personal communication). The North Carolina Department of Transportation (NC DOT) has begun to use RSCs (referred to as biofiltration conveyances [BFCs] by NC DOT) as retrofit SCMs along roadsides. One RSC was installed at the Alamance County, NC, I-85 Southbound Rest Area and extensively monitored for hydrology and water quality. Using the data collected from the site, this research aims to:

- i. Quantify the flow pathways of runoff entering the RSC,
- ii. Determine the ability of this RSC to mitigate stormwater runoff vis-a-vis predevelopment hydrology,
- iii. Quantify the ability of the RSC to remove nutrients and TSS from stormwater runoff, and
- iv. Identify pollutant removal mechanisms and design characteristics associated with nutrient and TSS reductions.

This work is critical in providing a benchmark for RSC performance.

4.3 Methodology

4.3.1 Site Description

The Alamance RSC was installed along an entrance ramp from the rest area (36.06° N, 79.54° W) during summer of 2013. The RSC's 1.6-ha watershed is 63% impervious, primarily consisting of parking areas and building rooftop (Figure 4-2a, Table 4-1). The parking spaces (0.76 ha) are directly connected to the inlet of the RSC. The underlying soil is composed of Wilkes (HSG D, K_{SAT} 0 to 0.25 mm hr⁻¹) soil series with 15 cm sandy loam covering 15 to 20 cm tight clay, overlying weathered diorite, gabbro, diabase, and gneiss bedrock. Runoff enters the 33.5-m RSC via a sewer grate and 61-cm concrete pipe. The RSC is comprised of three pool/riffles with an average system slope of 2.5% followed by a 2.9-m cascade drop into a series of three "wetland pools" of equal elevation (Figure 4-1). The sand media bed is 0.6 m deep with 0.46 m of Class 1 (diameter 15 to 30 cm) rip rap to stabilize the channel (Table 1). An exfiltration trench is located beneath the "wetland pools" such that water levels below the sand media will leave the system via exfiltration (Figure 4-1). The entire RSC was covered in 10 to 15 cm of composted hardwood mulch and seeded (Figure 4-2b).



(a)



(b)

Figure 4-2 Alamance County RSC watershed (a) and photo with monitoring weir visible (b)

Table 4-1 Alamance County RSC site description

	Cell 1	Cell 2	Cell 3	Cell 4
Contributing Watershed Area	1.6 ha			
Nearest Weather Station	KBUY-Burlington Alamance Airport			
% Imperviousness / % DCIA ¹	63% / 48%			
HSG / Infiltration Rate	D / 0.25 mm hr ⁻¹			
Sand Media Depth	0.61 m			
Rip Rap Depth	0.46 m			
Ponding Depth	0.46 m			
Length	5.8 m	6.1 m	6.7 m	14.6 m
Width	4.9 m	4.9 m	4.9 m	4.9 m
Surface Area	28.2 m ²	29.7 m ²	32.7 m ²	71.3 m ²
Contributing Run On Area	335 m ²	66 m ²	91.8 m ²	254 m ²
Average Slope	1.3 %	3.75 %	2.3 %	8.33%
Sand Media Storage	5.6 m ³	8.1 m ³	6.5 m ³	15.2 m ³
Rip Rap Storage	3.0 m ³	2.2 m ³	3.7 m ³	9.0 m ³
Pond Storage	3.42 m ³	4.9 m ³	6.1 m ³	8.0 m ³

¹ DCIA = directly connected imperviousness area

4.3.2 Hydrologic Monitoring

Once water enters an RSC, it can exit as surface flow, seepage (shallow interflow), evapotranspiration, and exfiltration. Surface flow is runoff leaving the RSC over the weir, where seepage out leaves via percolation through the sand media bed.

Exfiltrated water enters the parent soil. Surface flow and exfiltration were measured herein. Evapotranspiration was calculated using reference values measured at nearby weather stations (Table 4-1), and seepage was calculated by completing the water balance. The RSC was divided into four cells, with Cells 1 through 3 each

containing one pool/riffle series; Cell 4 comprised the “wetland pools” (Figure 4-1). Rainfall was measured by a tipping bucket rain gage located 5 m from Cell 4, and calibrated using a manual rain gage.

4.3.2.1 Surface Water

Runoff levels and velocities entering the RSC were recorded at 2-min intervals using an ISCO 750 area-velocity meter located 1 m within the 61-cm concrete pipe conveying water from the storm sewer grate to the RSC. Flow entering the RSC was calculated for each 2-min interval using Eq. 4-1.

$$Q = v \frac{r^2(\theta - \sin\theta)}{2E-3} \quad \text{Eq. 4-1}$$

where Q is the flow rate, in L/s

θ is determined by $2\arccos\left(\frac{r-h}{r}\right)$, in radians

r is the pipe radius in meters, 0.3 m

h is the height of the water in the pipe in meters

v is the velocity of the water, m/s

When ponded water created backwater in the inlet pipe, runoff entering the RSC was estimated using the SCS Curve Number Method (SCS, 1985) and Rational Method (ASCE, 1996), with the curve number and runoff coefficient estimated from known storm inflows. ISCO 730 bubblers were used to collect 2-min interval water depth measurements at the inlet and outlet monitoring weirs of the remaining RSC cells (Figure 4-1). The monitoring weirs located at the outlet of each pool consisted of compound weir with 13-cm 90-deg V-notch lower section and a 0.91-m broad crested upper section (Figure 4-2b). A compound 90-degree v-notch and broad crested weir equation was used to determine flow through the internal inlets and outlets of the RSC, using the water level above the invert of the weir (Eq. 4-2) for each 2-min interval.

$$Q = \begin{cases} 2.31h^{2.49} & h \leq 12.7 \\ 2.31h^{2.49} + 10L(h - 12.7)^{1.5} & h > 12.7 \end{cases} \quad \text{Eq. 4-2}$$

where Q is the flow rate, in L/s, when water level is h cm

L is the length of the broad crested weir, 0.91 m

Flow measurements were used to determine the peak flow reduction and overall volume reduction of the RSC system for each measured rainfall event.

4.3.2.2 Exfiltration

The media bed is designed to facilitate exfiltration into the parent soil, and eventually into the groundwater, similar to the function of bioretention media (Brown and Hunt, 2011). The exfiltration trench located beneath Cell 4 (Figure 4-1) was used for the estimation of exfiltration rates. Hobo™ pressure transducers were used to measure the height of the water in the sampling well located within the Cell 4's final pool, i.e., the height of the water in the media bed. Stored runoff pools within the media, and once the internal water level was below the top of the exfiltration trench, the water could only exfiltrate from the sides and bottom of the trench. Further water level decrease and associated volume reductions were attributed solely to exfiltration; volume changes were used to calculate the exfiltration rate. Regression analysis was used to determine the relationship between the volume of water exfiltrated and the stage of the water within the media. Exfiltration was then back-calculated over the entire storm event for water levels within each of the cells. Total exfiltration over the course of the rainfall event was calculated as the sum of exfiltration for each time increment.

4.3.2.3 Evapotranspiration

The vegetation within the system did not establish during the monitoring period, so evaporation rates were applied *only* when water was ponded on the RSC. Pan

evaporation values from KBUY-Burlington Alamance Airport in Burlington, NC (36.05 N, 79.47 W), located 6.4 km from the RSC, were used.

4.3.2.4 Seepage

Seepage was calculated using all the previously determined inflow and outflows; horizontal sand seepage rates through the sand media were estimated from the well data. For each cell, the following water balance was calculated using Eq. 4-3

$$\Delta Storage = V_{surf,in} + V_{seep,in} + RunOn - V_{surf,out} - V_{seep,out} - ET - Ex \quad \text{Eq. 4-3}$$

where $\Delta Storage$ is the change in storage

V_{surf} is the surface volume in and out of the cell

V_{seep} is the seepage volume in and out of the cell

Q_{RO} is the precipitation and runoff entering the cell

ET is the calculated evaporation

Ex is the measured exfiltration

RSC storage for each cell was determined based on stage-storage calculations. Sand was estimated to have 30% drainage porosity and the riprap has 25% drainage porosity (Stephens et al., 1998).

4.3.2.5 Estimating Pre-development Hydrology

Pre-development runoff volumes and flows of each storm event were calculated using the SCS Curve Number Method (SCS, 1985) and the Rational Method (ASCE, 1996). Vegetation in the 1.6-ha watershed is un-grazed wooded or pine forests. A predevelopment SCS curve number for the watershed was estimated as 77 (considering HSG D soils), and a rational runoff coefficient of 0.15 was chosen. Given the calculated runoff volume and peak flow, a step-function described in Eq. 4-4, (Malcom, 1989), was used to estimate the center-weighted pre-development hydrograph for each storm event.

$$q_i = \begin{cases} \frac{Q_p}{2} \left[1 - \cos\left(\frac{\pi t_i}{T_p}\right) \right] & \text{for } t_i \leq 1.25T_p \\ 4.34Q_p \exp\left(-1.30 \frac{t_i}{T_p}\right) & \text{for } t_i > 1.25T_p \end{cases} \quad \text{Eq. 4-4}$$

where q_i is the respective flow rate for time t_i m^3/s

Q_p is peak design flow rate in m^3/s

T_p is the time to Q_p in seconds, calculated by $T_p = \frac{V}{1.39Q_p}$

V is the total runoff volume in m^3

Additionally, undeveloped watersheds show clear evidence of three different flow pathways contributing to a storm hydrograph: 1) surface runoff, 2) groundwater surge, and 3) shallow interflow (Williams and Pinder, 1990; Brown et al., 1999; Kendell et al., 2001). To truly achieve predevelopment hydrology, all three pathways should be considered. Previous studies of RSC systems suggest that the surface runoff and shallow interflow (also referred to as seepage) pathways are present at the outlet of RSCs (Brown, 1999; Chapter 3). Stable isotopes have been used in the past to distinguish between water from that rainfall event and stored water from a previous event in SCMs (Cizek and Hunt, 2013). Samples were taken in the Spring 2014 from the inflow and the outflow of the system using ISCO 6712 auto samplers over the course of the storm hydrograph. The cumulative inflow sample and samples at select points within the outflow hydrograph underwent analysis for deuterium concentration at Duke DEVIL Labs in Durham, NC. Deuterium levels over the course of the hydrograph were used to determine if the initial initially water leaving the RSC was water from a previous rainfall event, thus mimicking the predevelopment groundwater surge pathway.

4.3.3 Water Quality Monitoring

Water quality samples were taken from the surface water at the inlet and the outlet of each cell. Pollutant concentrations and total pollutant loadings were calculated using flow volumes as described in the section above.

4.3.3.1 Field Measurements

ISCO 6712 automated samplers collected flow-weighted composite samples at the sampling sites indicated in Figure 4-1 to determine event mean concentrations (EMCs) for each storm event. Samples were collected within 36 hours of the storm event, placed on ice, and submitted to the NCSU Center for Applied Aquatic Ecology for Total Suspended Solids (TSS), Total Phosphorus (TP), Ortho-Phosphate (OP), Nitrate/Nitrite-Nitrogen (NO₃), Total Kjeldahl Nitrogen (TKN), and Ammonium-Nitrogen (TAN) analysis. Total Nitrogen (TN) was calculated using Eq. 4-5

$$[TN] = [TKN] + [NO_3/NO_2 - N] \quad \text{Eq.4-5}$$

Additionally, pH and temperature were measured for each sample. Recorded EMCs show pollutant concentration reduction throughout the system, providing valuable insight into possible pollutant removal processes occurring within the RSC.

4.3.3.2 Loading Calculations

The total loading of pollutants exiting the system measures RSC pollutant contribution to receiving waters. The overall pollutant loading was calculated for each contaminant measured in field using Eq. 4-6

$$TL = EMC \sum V_{Weir,t} \quad \text{Eq. 4-6}$$

where TL is the total loading of a pollutant for one storm event (mg)

EMC is the effective mean concentration for the pollutant (mg/L)

$V_{\text{Weir},t}$ is the volume (L) measured at the specified at time t , for all t 's over the course of a storm event.

4.3.4 Statistics

Water quality and hydrologic data were tested for normalcy using the Sharpiro-Wilk test and visual assessment. The data were uniformly non-normal; therefore, non-parametric statistical methods were used for further comparative analysis.

Differences in inflow and outflow volume, flows, pollutant concentrations, and pollutant loads were tested for significance using the Wilcoxon Rank-Sum Test. Differences in seasonality was tested using the Kruskal-Wallis non-parametric ANOVA. For all statical analysis, the data was significant when Type I error (α) was less than 0.05.

4.4 Results

4.4.1 Hydrologic Performance

The site received 978 mm of total monitored rainfall between July 10, 2013, and June 10, 2014, resulting in 43 inflow-producing rainfall events. The largest event, occurring on September 1, 2013, included 81 mm of total precipitation falling at maximum intensity of 74 mm/h. This event produced in 660 m³ of runoff at a peak flow of 246 L/s. The RSC discharged 235 m³ of surface outflow at a maximum rate of 102 L/s, effectively reducing surface runoff by 57% and peak flow by 68%. Over the course of the monitoring period, median runoff and peak flow reductions were 84% and 80%, respectively (Table 4-2). The three cells prior to the cascade significantly reduced surface volume and flow with each additional cell, except within Cell 3, where no significant change was observed. A 36% median *increase* in surface volume was observed between the inlet and outlet of Cell 4. This is likely because of the frequently high subsurface water levels present in the media of Cell 4, resulting in little additional subsurface storage for the seepage entering from Cell 3. Ultimately, the addition of the “wetland pools” (Cell 4) to the RSC mostly decreased

median hydrologic performance from 89% surface volume and 85% peak flow reduction to 84% surface volume and 77% peak flow reduction.

Table 4-2 Median measured volume and peak flow over each weir. Bold values are statistically significant based on $\alpha = 0.05$.

	Volume			Peak Flow		
	Median (m ³)	Cell Reduction	Cum. Reduction	Median (L/s)	Cell Reduction	Cum. Reduction
Inlet	129.5			80.4		
Outlet 1	78.6	30%	30%	33.7	55%	55%
Outlet 2	29.0	61%	79%	23.2	44%	69%
Outlet 3	15.9	58%	89%	14.2	47%	78%
Outlet 4	20.9	-36%	84%	15.0	-6%	77%

As predicted by Brown (2009) and observed in Chapter 3, 77% of the runoff that entered the RSC was effectively converted to subsurface seepage (cognate to shallow interflow) (Table 4-3). As the surface water infiltrated into the media, the amount of water leaving each cell as subsurface seepage increased progressively through the RSC until Cell 4. The subsurface geometry of Cell 4 retained water in the media, thus restricting some subsurface seepage from leaving the RSC (Figure 4-1). Despite the increase in surface flow, the retention of runoff in Cell 4 did promote some (albeit slow) exfiltration into the parent soil (nearly 280 m³ over the course of the monitoring period) (Table 4-3). Volumetric exfiltration rate regression showed a high level of variability, likely related to the amount of clay present in the parent soils. Exfiltration rates are exponentially influenced by soil water content (Mahmood-ul-Hassan et al., 2013; de Faria and Bowen, 2003), which can vary in clay soils depending on how recently the soil was saturated. Ultimately, an exponential relationship was found as described by Eq. 4-7

$$\text{Vol}_{\text{EXFIL}} = 0.0497 \exp(3.9794d) \quad R^2 = 0.225 \quad \text{Eq. 4-7}$$

where Vol_{EXFIL} is the volume of water exfiltrated in $L/hr/m^3$
 d is the water level in m above the base of media

A negligible $24 m^3$ of water were evaporated when water was ponded within the pools of the RSC. Based on studies done in bioretention cells, it is expected that this number could increase to 30% or 40% of the overall RSC inflow with the presence of established vegetation within the pools (Brown et al., 2013).

Table 4-3 Fraction of inflow and outflow sources and fates for each RSC cell.

		INFLOW			OUTFLOW			
		Surface	Run On	Seep	Surface	Seep	ET	Exfil
Cell 1	<i>Sum</i>	0.91	0.04	NA	0.64	0.32	0.00	0.00
	<i>Fall</i>	0.92	0.03	NA	0.70	0.27	0.00	0.00
	<i>Win</i>	0.92	0.03	NA	0.76	0.19	0.00	0.00
	<i>Spr</i>	0.92	0.03	NA	0.53	0.39	0.00	0.00
	Total	0.93	0.03	NA	0.60	0.35	0.00	0.00
Cell 2	<i>Sum</i>	0.64	0.01	0.32	0.22	0.74	0.00	0.00
	<i>Fall</i>	0.70	0.01	0.27	0.10	0.84	0.00	0.00
	<i>Win</i>	0.76	0.01	0.19	0.30	0.65	0.00	0.00
	<i>Spr</i>	0.53	0.01	0.39	0.13	0.82	0.00	0.00
	Total	0.60	0.01	0.35	0.30	0.66	0.00	0.00
Cell 3	<i>Sum</i>	0.22	0.01	0.74	0.13	0.85	0.00	0.00
	<i>Fall</i>	0.10	0.01	0.84	0.07	0.89	0.00	0.00
	<i>Win</i>	0.30	0.01	0.65	0.13	0.82	0.00	0.00
	<i>Spr</i>	0.13	0.01	0.82	0.03	0.91	0.00	0.00
	Total	0.30	0.01	0.66	0.15	0.81	0.00	0.00
Cell 4	<i>Sum</i>	0.13	0.03	0.85	0.26	0.70	0.00	0.03
	<i>Fall</i>	0.07	0.03	0.89	0.11	0.95	0.00	0.04
	<i>Win</i>	0.13	0.03	0.82	0.07	0.86	0.00	0.05
	<i>Spr</i>	0.03	0.03	0.91	0.04	0.82	0.00	0.02
	Total	0.15	0.03	0.81	0.20	0.77	0.00	0.03

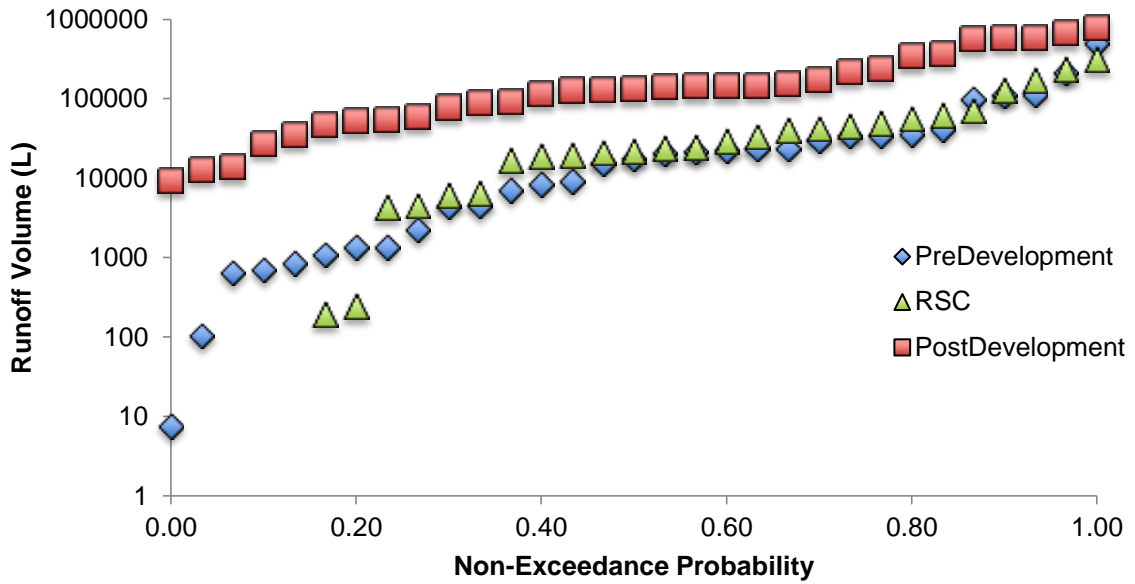
The data were tested for seasonal influences using the following criteria – Summer was considered Jun 1 through Sept 14, Fall was Sept 15 through Dec 14, Winter

was Dec 15 through Mar 14, and Spring was Mar 15 through Jun 1 (Table 4-3). Inflow volume and peak flows did not show significant differences among the seasons. There was a significant difference between the fraction of water leaving Cell 1 as surface flow in the winter (median = 0.76) and spring (0.53). This is unexpected given that the inflow volume and peak flow is relatively constant. One possible is the frequent freezing temperatures during winter 2013, thus creating occasional impervious layers of ice over the surface and in pore spaces of the media. Three of the eight winter rainfall events occurred on days with minimum temperature below 0°C. Median surface flow reduction for these three events in Cell 1 was 17%. Median surface reductions from the other five “warmer” winter events were 34%, much more similar to that observed during other seasons (36% in summer, 30% in fall, 47% in spring) (Table 4-3). Similarly, this phenomenon may have occurred in the other cells, but was less apparent than in Cell 1, where the greatest overall volumetric conversion from surface flow to seepage occurred. The fraction of surface flow leaving Cell 4 was also significantly greater during summer than fall, winter, or spring - a median 26% as compared to 11%, 7%, and 4%, respectively. Summer also experienced the longest duration of high subsurface water levels. Median pre-storm Cell 4 subsurface water level was 1.31 m above the bottom of the media, or 0.21 m from the invert of the weir, as compared to 0.58 m, 1.03 m, and 1.10 m in the fall, winter, and spring, respectively. Thus, the additional surface flow from Cell 4 is likely related to the reduced subsurface storage available due to high subsurface saturation levels.

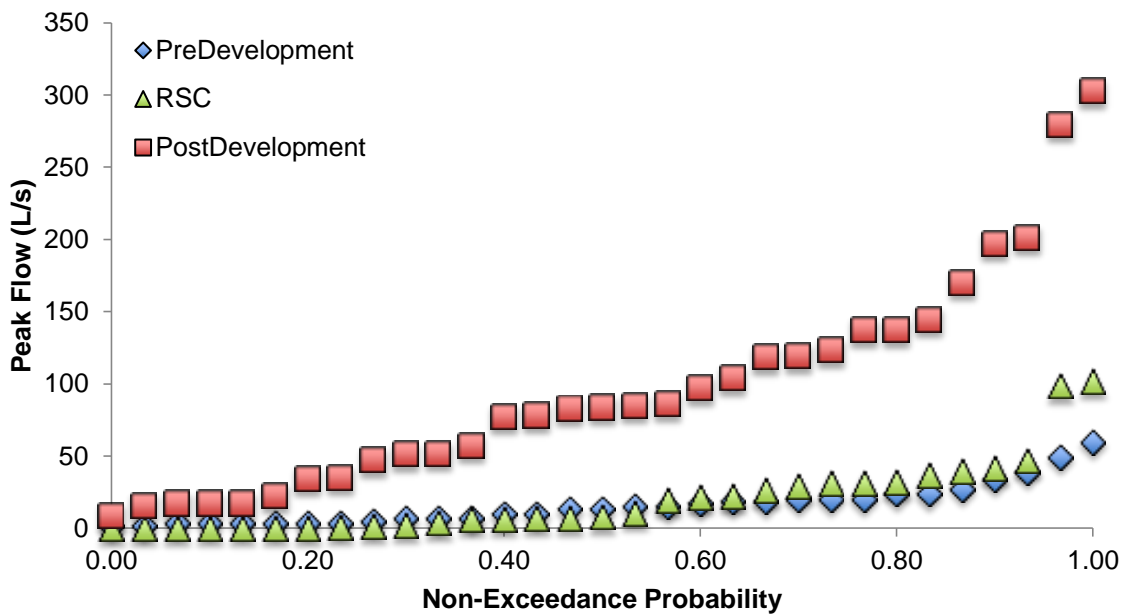
Modeled predevelopment, and measured post-development runoff and RSC outlet volumes and peak flows were compared for each monitored storm event (Figure 4-3). Runoff volume and peak flow from the RSC outlet were much less than or similar to modeled predevelopment conditions for 95% of the time. As these are the two parameters that drive hydrograph shape, the data strongly suggest that RSCs can mimic the overall predevelopment hydrology. Both modeled predevelopment

runoff and RSC outlet flows and volumes are significantly less than post-development conditions, reinforcing the need for an SCM to mitigate runoff from such development.

Inflow and partitioned outflow samples from five rainfall events April 2014 through June 2014 underwent deuterium isotope analysis to determine the age of the water leaving Cell 4. Samples displayed initially high deuterium concentrations, relative to inflow, progressing towards concentrations similar to and lower than those found in the inflow as more water left the RSC (Figure 4-4). Processes like evapotranspiration, plant uptake, and microbial digestion preferentially choose lighter single neutron protium atom over the heavier deuterium atom (Barnes and Allison, 1988; Friedmand et al., 1964). Therefore, water stored in the cell between storm events (also referred to as pre-event water), which has undergone some level of evaporation and microbial digestion, is enriched in deuterium as compared to the precipitation and inflow. Median ratios of deuterium outflow and inflow concentrations for the first 55 m³, 110 m³, and > 110 m³ of RSC outflow are 0.69, 0.98, and 1.01, respectively. Although statistical significance was limited due to the amount of samples available for said analysis, the first 55 m³ of water released from the RSC appeared to be composed, at least in part, of pre-event water. Beyond the surface runoff and shallow interflow (or subsurface seepage) pathways evident in the water balance described herein, RSC may also be able to mimic the groundwater surge pathway when subsurface runoff retention is present. Therefore, in addition to mimicking overall predevelopment shape (volume and peak flow), RSCs also provide opportunities for all predevelopment hydrograph pathways described by Cizek and Hunt (2012).



(a)



(b)

Figure 4-3 Modeled predevelopment, post-development, and RSC (a) outflow volume and (b) peak flow for each monitored rainfall event.

4.4.2 Water Quality Performance

During the course of the monitoring period, 20 events were sampled for water quality performance analysis. Influent nutrient concentrations varied widely based on activity within the watershed. Median TN concentrations were 2.4 mg/L, but ranged from 1.63 mg/L to 9.96 mg/L (Table 4-4). High TN concentrations often corresponded with high Total Kjeldahl Nitrogen (TKN), Total Ammoniacal Nitrogen (TAN), and, in most cases high Total Phosphorus (TP) and ortho-Phosphate (OP) concentrations. It is known that the landscaping crew fertilized portions of the watershed in October and March, and some instances of high nutrient concentrations corresponded with these events. On the other hand, some instances of high concentrations of nutrients occurred mid-winter and are likely not related to fertilizers (See Appendix B). The nutrient source of the winter spikes remains unknown.

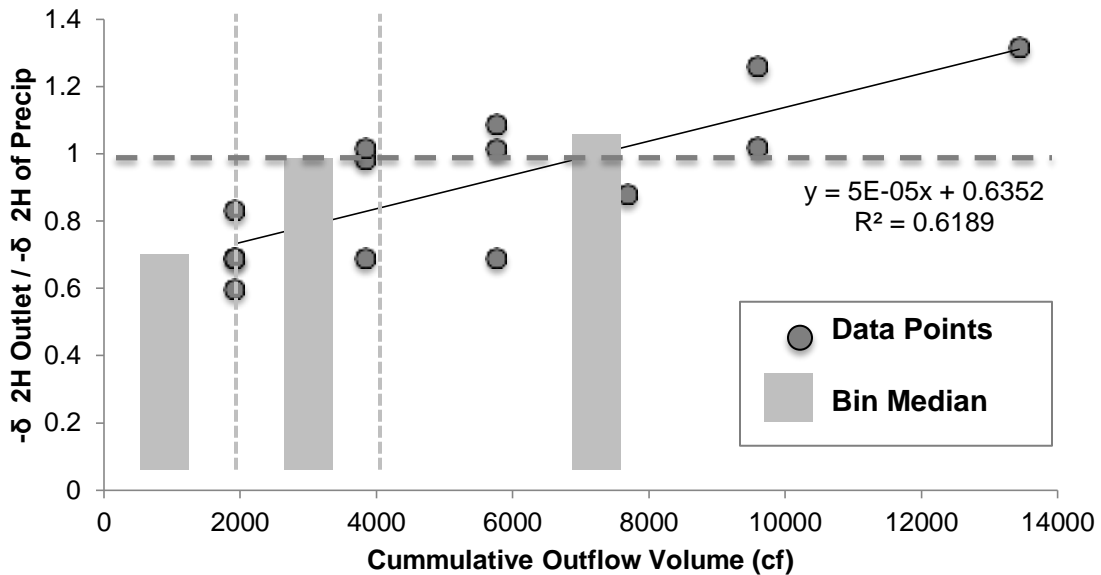


Figure 4-4 Summary of the deuterium isotope concentration ratio between outflow and inflow as compared to cumulative outflow. A ratio of 1 or higher suggests the water is predominantly event water.

Despite the variable inflow nutrient loadings, the RSC relatively consistently removed pollutants from surface flows. The RSC significantly reduced concentrations of TN by 30%, TKN by 37%, TAN by 33%, TP by 28%, and TSS by 72%. The first cell acted as a forebay, in that more than 25% of the inflow TSS was removed here, but no significant nutrient reductions occurred. TSS continued to be successively removed as surface flow moved from cell to cell. Most of the nutrient reduction occurred in Cell 2, with slight increases in NO₃ (0.02 mg/L or 8%) and TAN (0.03 mg/L or 14%) in Cell 3. This increase in nutrients may be evidence of the relatively high organic content in the media and the large amounts of composted wood chips present on the surface being flushed through the system. As this particular cell is further downstream and more difficult to access by the public, the nutrient increase is unlikely to be due to dumping, pet waste, etc. It is also unlikely related to fertilizer application, as the increase is isolated to Cell 3 and not observed throughout the entire RSC. Despite the increase in concentration, significantly smaller concentrations of NO₃ and TAN left Cell 3 in the spring (0.21 mg/L and 0.12 mg/L, respectively) than in summer (0.45 mg/L and 0.31 mg/L, respectively). TAN was further reduced in Cell 4, possibly as a result of additional aeration through the cascade entering the pools, oxygenating water for nitrification. Significant TP reduction also occurred in Cell 4. The overall contribution of the “wetland pools” appeared to be further nutrient and TSS removal from the surface water, but not necessarily greater improvement than measured in Cell 2, which was well drained. It is possible that adding vegetation the “wetland pools” may increase microbial activity, and subsequent microbial nutrient reductions. However, runoff leaving Cell 3 is not further reducible in a wetland environment (Moore et al., 2011).

Pollutant loadings were progressively reduced throughout the first three cells of the RSC (Table 4-4). This well-drained RSC section removed 14.8 kg of TN, 2.62 kg of TP, and 347 metric tons of TSS from the surface flow over the course of the monitoring period, equivalent to a median load reduction of 86% for TN and TP, and

95% for TSS. The addition of the “wetland pools” modestly increased loadings, due to the increase in surface outflow at times of high subsurface saturation. Overall, the RSC still reduced 81%, 84%, and 94% of the TN, TP, and TSS load. This corresponds to storm surface discharge loads of 2.5 kg TN, 0.57 kg TP, and 29.2 metric tons of TSS.

Table 4-4 Median pollutant event mean concentrations and loadings at each weir over the course of the monitoring period.

		TN		TKN		NO3		TAN		TP		OP		TSS	
		Conc (mg/L)	Load (kg)	Conc (mg/L)	Load (kg)	Conc (mg/L)	Load (kg)	Conc (mg/L)	Load (kg)	Conc (mg/L)	Load (kg)	Conc (mg/L)	Load (kg)	Conc (g/L)	Load (m.ton)
Inlet	<i>Sum</i>	1.84	471.5	1.63	425.3	0.21	87.3	0.20	47.2	0.33	71.6	0.22	47.1	39.5	6665
	<i>Fall</i>	3.95	455.9	3.08	355.4	0.56	100.5	0.88	86.7	0.66	75.9	0.50	57.9	71.2	10320
	<i>Win</i>	2.68	1074.4	2.35	942.6	0.23	78.9	0.35	75.2	0.58	111.6	0.20	75.7	90.1	46931
	<i>Spr</i>	3.14	1155.4	2.93	999.3	0.23	92.7	0.33	123.7	0.46	208.2	0.19	73.9	77.0	32413
	Total	2.40	907.5	2.17	782.1	0.24	87.3	0.35	86.7	0.44	111.6	0.22	73.2	69.1	10713
Outlet 1	<i>Sum</i>	2.03	276.5	1.79	209.6	0.30	66.8	0.21	68.5	0.43	41.7	0.30	22.3	11.3	3325
	<i>Fall</i>	2.68	752.6	2.40	695.9	0.28	56.7	0.55	172.1	0.44	106.8	0.17	55.0	64.6	37357
	<i>Win</i>	1.54	233.4	1.30	185.2	0.30	48.3	0.34	59.0	0.53	104.5	0.35	82.3	14.2	6086
	<i>Spr</i>	2.14	655.2	1.90	625.8	0.19	29.5	0.32	68.5	0.31	104.0	0.17	40.5	29.6	13875
	Total	2.21	525.0	1.96	477.8	0.25	47.9	0.34	69.1	0.44	93.2	0.22	51.4	29.4	6044
Outlet 2	<i>Sum</i>	1.74	92.2	1.49	73.3	0.24	19.0	0.21	11.2	0.40	15.7	0.31	12.0	9.9	1786
	<i>Fall</i>	1.54	62.3	1.28	54.5	0.31	7.8	0.22	14.4	0.47	23.9	0.36	17.6	33.2	1776
	<i>Win</i>	2.18	282.1	1.90	268.6	0.20	13.5	0.32	35.8	0.51	46.7	0.25	10.4	72.2	14347
	<i>Spr</i>	1.39	220.6	1.22	199.4	0.16	21.3	0.09	10.6	0.28	42.2	0.14	19.1	41.7	5711
	Total	1.72	102.5	1.43	82.9	0.24	15.8	0.21	14.6	0.41	25.3	0.22	14.8	38.2	1879
Outlet 3	<i>Sum</i>	3.80	96.4	3.36	88.9	0.45	10.9	0.31	18.6	0.63	10.1	0.22	3.8	12.8	1073
	<i>Fall</i>	1.54	47.4	1.13	35.0	0.31	10.3	0.24	8.6	0.49	15.0	0.38	11.6	22.4	914
	<i>Win</i>	2.20	112.1	1.96	105.5	0.24	6.6	0.30	10.2	0.44	14.3	0.25	3.9	32.5	2343
	<i>Spr</i>	1.39	146.7	1.17	127.5	0.21	19.2	0.12	9.7	0.26	27.2	0.13	12.0	27.6	2439
	Total	1.92	63.1	1.57	55.9	0.26	10.6	0.24	9.1	0.41	14.9	0.22	6.8	22.0	952
Outlet 4	<i>Sum</i>	1.86	116.8	1.52	88.0	0.35	28.9	0.29	16.2	0.30	17.0	0.19	11.8	10.0	466
	<i>Fall</i>	1.68	56.1	1.43	38.0	0.46	15.0	0.25	9.1	0.41	16.3	0.31	11.3	14.3	686
	<i>Win</i>	1.50	253.4	1.25	215.0	0.22	38.4	0.20	23.4	0.35	52.6	0.18	34.5	18.7	2608
	<i>Spr</i>	1.44	146.2	1.18	120.0	0.30	26.2	0.13	10.0	0.26	26.7	0.15	13.2	17.3	1706
	Total	1.76	101.4	1.43	79.7	0.29	20.3	0.20	9.8	0.34	19.3	0.19	11.5	11.6	1050

4.5 Discussion

The Alamance County RSC met traditional SCM goals of peak flow mitigation and volume reduction and LID goals of mimicking the predevelopment hydrograph. Surface volume and peak flow reductions exceeded that frequently observed in other media-based (Hunt et al., 2006; Passeport et al. 2009) or conveyance (Winston et al., 2012) SCMs located in HSG D soils. Furthermore, the outflow volume and discharge rates were strikingly similar to that modeled for the watershed under predeveloped conditions. RSCs also exhibit all flow pathways present in predeveloped watersheds, namely shallow interflow (seepage) and groundwater surge. In fact, nearly 80% of the RSC hydrograph is comprised of these two pathways, a fraction within the range observed in undeveloped watershed (Brown et al., 1999; Kendell et al., 2001; Soulsby, 1995; Wenninger et al., 2004; Williams and Pinder, 1990). Surface flow could be further reduced through encouraging evapotranspiration via an established plant community and through the installation of exfiltration trenches beneath any appropriate cell.

The greatest pollutant reductions were observed in TN, TKN, TP, and TSS. TKN concentrations comprised the majority of TN. TSS and associated TP, as well as organic nitrogen, a large component of TKN, are effectively removed via physical pollutant removal mechanisms such as sedimentation and filtration, which are likely to be the main treatment processes occurring as surface water flows through the riffle pools. Additionally, observations of increasing surface flow in downstream pools, as well as measurements made at other RSC sites (Chapter 3), suggest that water leaving the system as surface water may have experienced some subsurface filtration and reemerged as surface water further down in the SCM. Significant reductions in TAN suggest some adsorption or nitrification may be occurring throughout the system, but there is not any evidence of denitrification as NO₃ is not significantly reduced. This is a bit surprising as the “wetland pools” harbor conditions

that seem suitable for denitrification to occur. Additionally, another RSC in Maryland (MD) exhibiting wetland-like conditions reduced NO₃ by 35% on average (Browning, 2009), despite smaller inflow concentrations. Four out of five rainfall events with inflow nitrate concentrations equal to or less than those coming into the Alamance Cell 4 were reduced by 20% to 60%. The main differences between the Alamance RSC and the MD site is (1) the age – the MD was 3 years established at the time of monitoring – and (2) the density, diversity, and establishment of vegetation – the Alamance site had little to no vegetation throughout the entire monitoring period where the MD site was planted as an Atlantic White Cedar habitat. Plants may be needed to provide denitrifying bacteria with an available carbon source, and the woodchips in the media may not be sufficiently reduced within the first year of the RSC establishment. Previous studies have observed relationships between vegetation density and health with denitrification rates (Bachand and Horne, 2000; Liu et al., 2011; Lucas and Greenway, 2008). It is possible, then, that NO₃ reductions in the RSC could improve with the planting and establishment of vegetation.

Another important consideration for water quality performance is that most of the water leaving the system is leaving as shallow interflow. If similar pollutant removal mechanisms occur to RSC subsurface seepage, then median pollutant loading reductions for this RSC would decrease to 30% TN, 27% TP, and 72% TSS. Research has shown that in riparian buffers, water traveling via shallow interflow undergoes a higher degree of physical, chemical, and in proper conditions, biological treatment process than observed in surface flow (Cooper, 1990; McDowell et al., 1992; Lowrance et al., 2000; Peterjohn and Correll, 1984). Chapter 5 explores nitrogen reduction in RSC seepage in a well-drained RSC (equivalent to Cells 1 through 3) during the winter. TKN from this RSC underwent reductions similar to that observed in the Alamance surface flow. Additional reduction of NO₃ was observed in the subsurface seepage, suggesting an overall higher reduction of TN, and,

therefore, smaller total TN loadings than predicted herein. To truly understand the ability of RSCs to mitigate water quality, however, pollutant removal mechanisms in RSC seepage should be explored in the field for a variety of hydrologic and seasonal conditions.

RSCs have the potential of being very adaptable, depending on design goals for a specific project. As stated herein, for example, the addition of exfiltration trenches can reduce surface outflow volume via increasing exfiltration. These trenches also may encourage a wetter, more slowly drained system observed in Cell 4, as opposed to a well-drained system experienced in Cell 1 through 3, particularly in tight clay soils. Well-drained systems provide greater surface volume reduction, with available soil pore space to encourage the greatest amount of subsurface flow. Wetter systems, on the other hand, provide opportunities for exfiltration, and if well vegetated, will likely provide additional pollutant removal mechanisms, namely nitrification/denitrification. It may make sense to create wetter cells further upstream (i.e., Cells 2 and 3), with well-drained cells at the tail-end of the RSC (Cell 4). In tight soils, for example, this could be done by creating deep exfiltration trenches in the sand media below Cells 1 through 3, while designing the media in Cell 4 to drain directly out of the RSC (as opposed to creating a trench). In this way, the RSC exhibits the water quality benefits of wetland-like conditions, but the additional surface flows caused by subsurface saturation can be re-converted to seepage before the RSC discharges to receiving waters.

The number of cells used is somewhat flexible, and has a clear connection to performance. This research suggests a minimum of three sequential cells with slope less than 5%. The first cell acts similar to a forebay by collecting larger sediment, and very little nutrient processing occurred. However, there is potential for nutrient processing in the subsequent two or more cells. Despite slight increases in nutrient concentrations, the third cell in the Alamance RSC reduced overall pollutant loadings

because of its ability to reduce surface runoff, and, therefore, was valuable to this RSC's performance. It should be noted that sediment accumulation was observed in the first cell resulting in some loss of storage. This is likely to continue over the life of the RSC, unless addressed by regular maintenance. Subsequent cells would also provide a safety factor for maintaining RSC hydrologic and water quality performance as the RSC changes with age, particularly if the RSC is not properly maintained.

4.6 Conclusion

Despite the challenge of being located in HSG D soils, the Alamance RSC was able to significantly reduce volume and peak flow, as well as provide opportunity to mimic the predevelopment hydrographs and flow pathways. Additionally, the Alamance RSC provided physical pollutant removal, leading to significant reductions in surface flow TSS, TKN, and TP concentrations, similar to or greater than that observed by other media-based systems in tight soils (Hunt et al., 2006; Passeport et al. 2009; Winston et al., 2012). Further nutrient removal potential exists if a plant community is established. With careful consideration of design goals and objectives, RSCs can be a valuable tool for managing the detrimental affects of stormwater runoff from urban and suburban development.

4.7 Acknowledgements

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5. Using In Situ Ultraviolet-Visual Spectroscopy to Measure Subsurface Nitrogen Concentrations in Seepage through Regenerative Stormwater Conveyance (RSC)

5.1 Abstract

Regenerative stormwater conveyance (RSC) mitigates stormwater runoff by converting surface flow to subsurface seepage using a series of pools and riffles built over a sand media bed. RSC seepage travels slowly through RSC media and exits the RSC beneath the outlet weir. Previous studies on RSC pollutant mitigation have focused on surface flow discharges from the RSC. To date, no known research has been conducted on pollutant contributions of RSC seepage, despite the fact that this water also enters receiving waters. This research uses in-situ ultraviolet-visual spectroscopy to measure nitrogen in seepage during simulated storm events at a field-scale RSC in Raleigh, North Carolina. PLSR models of good fit (Nash-Sutcliffe coefficient > 0.80) were produced for nitrate and total Kjeldahl nitrogen (TKN), but not for total ammoniacal nitrogen. Early storm simulations revealed some initial nutrient flushing, which subsided by the third simulation. Subsurface seepage concentrations nitrate and TKN concentrations were reduced 30% and 22% relative to storm inflow concentrations. Nitrogen reductions in sampling wells progressed over time, indicating that biological activity contributed, at least in part, to nitrogen reductions. Nitrogen is better removed in seepage than in surface flow; however, due to the high volume of runoff converted to seepage, nitrogen discharge loading in seepage can be larger than that of surface flow. Further research is needed to examine subsurface pollutant reductions under varying hydrologic and seasonal conditions.

5.2 Introduction

Nutrient loading to water bodies has resulted in severe degradation of coastal ecosystems, contributing to economic, aesthetic, recreational, and public health ramifications for humans (NRC, 2000). Nitrogen is of particular concern in coastal areas, especially in North Carolina. When coastal waters become over-enriched with nitrogen, eutrophication can occur, such that organic productivity increases causing changes to the ecosystem (Nixon, 1995). Eutrophication in coastal areas can cause (sometimes toxic) algal blooms, loss of habitat, changes in species distribution, and hypoxia (i.e. dead zones) (NRC, 2000). Nitrogen species directly available to vegetation (including algae) include ammonium ($\text{NH}_4\text{-N}$) and nitrate ($\text{NO}_3\text{-N}$). However, increases in concentrations of other nitrogen species may also drive production of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, causing similar detrimental effects (Figure 5-1).

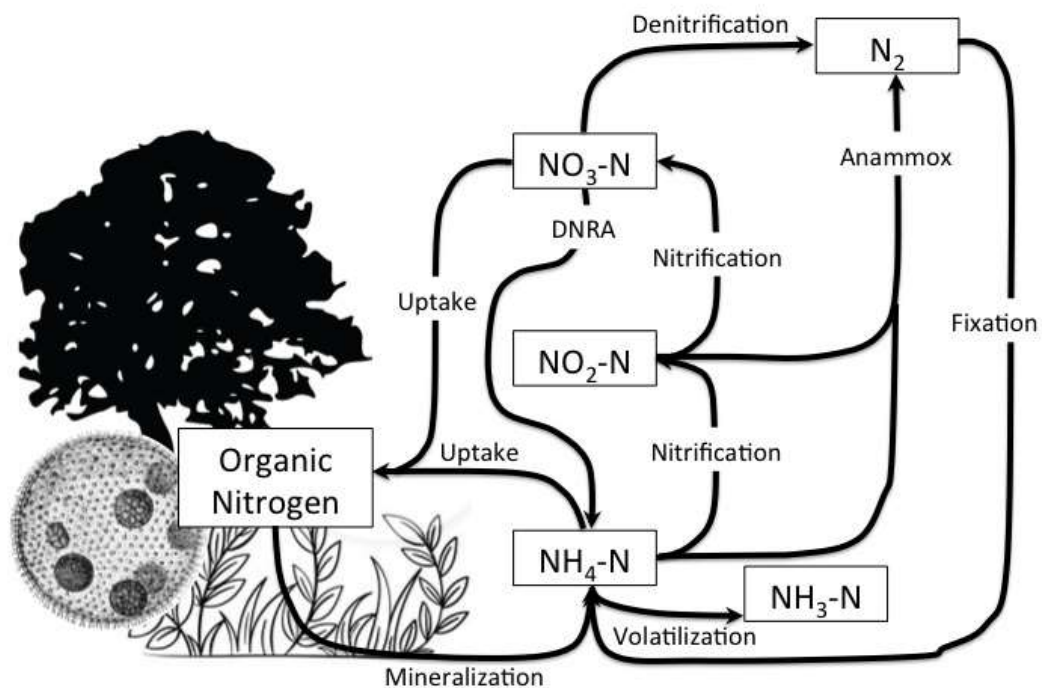


Figure 5-1 Nitrogen cycle. Note that an increase in nitrate ($\text{NO}_3\text{-N}$) or ammonium ($\text{NH}_4\text{-N}$) will also increase more organic nitrogen (i.e. organic matter), and has been linked to many detrimental ecosystem effects.

Nitrogen sources to coastal areas expand far inland. Increases in applied fertilizer on agricultural fields and large livestock productions produce excess nitrogen that enters inland streams via stormwater runoff or irrigation drainage (Isermann, 1990; NRC, 2000). Urban sources of nitrogen, namely fossil fuel combustion, also play a major role in increased nitrogen concentrations in coastal areas through atmospheric nitrogen deposition (NRC, 2000). Anthropogenic nitrogen fixation has increased 2- to 3-fold over the past 40 years, and continues to grow (Galloway et al., 1995; Holland et al., 2005). Collaborative efforts, including regulation, education, source reduction, and source management, are being put forth to try to reduce nitrogen inputs across the United States (NRC, 2000; MEA, 2005; Conley et al., 2009).

Some stormwater control measures (SCMs) receiving runoff from agricultural, suburban, and urban watersheds can reduce nitrogen loadings to receiving waters (Davis et al., 2006; Hsieh et al., 2007; Passeport et al., 2009; Hathaway and Hunt, 2010; Collins et al., 2010; Moore et al., 2011). $\text{NH}_4\text{-N}$ and organic nitrogen are ions with the ability to sorb to soil and other particulates (Vaze and Chiew, 2005). When associated with particles, these species can be removed from the water column via sedimentation and filtration, with the possibility of being re-suspended or exchanged with another ion. Nitrogen removal from the system requires long-term plant uptake or biotransformation. Regenerative stormwater conveyance (RSC) is a new vegetated, media-based approach to stormwater management. Recently credited as an SCM in Maryland (MD Department of the Environment, 2014), RSCs are open channel systems consisting of a porous media bed with a series of riffle/weir step pools (Figure 5-2). Similar to other media-based SCMs, the bed material has a high hydrologic conductivity to promote infiltration into the media bed, where filtration, sorption, and biotransformations can occur. Unlike bioretention media (Hunt et al., 2012), RSC media includes 20% to 30% shredded hardwood mulch to serve as a carbon source for microbial metabolism (Anne Arundel County Department of Public Works, 2012). The riffle/pool geometry absorbs energy and retains water by

promoting ponding in shallow pools and slowing water to non-erosive flows. A native plant community may also increase both water quality and hydrologic benefits through plant uptake of nutrients and evapotranspiration.

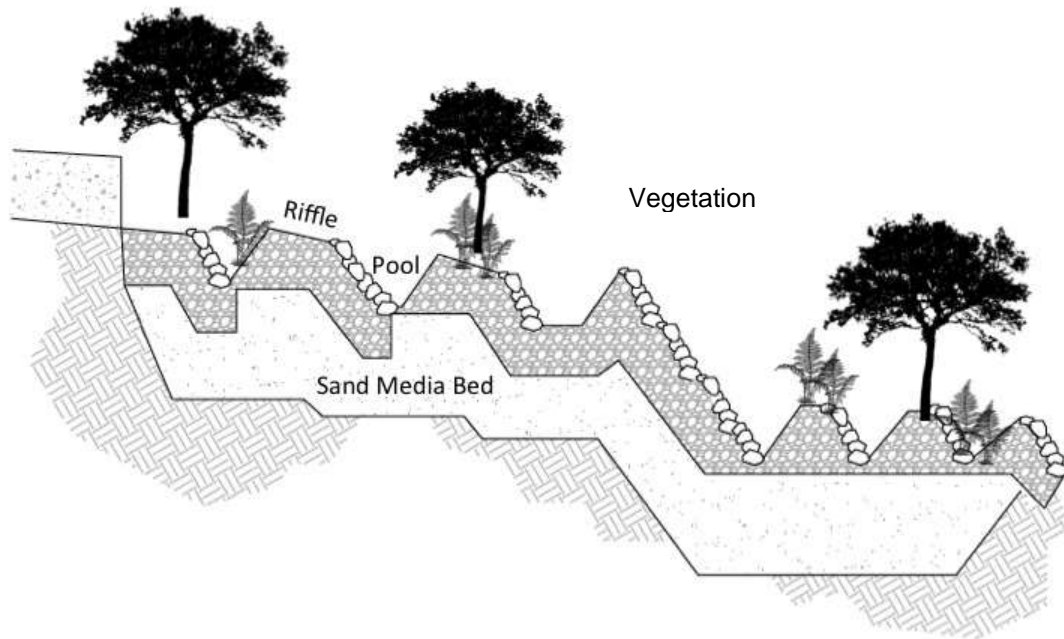


Figure 5-2 RSC profile (typ.), including major design features such as riffles and pools, sand media bed, and native vegetation

RSCs are designed to mitigate stormwater runoff and associated pollutants. During small rainfall events, water is expected to exit the system as seepage, or infiltrated surface water percolating through the RSC sand media bed (cognate to shallow interflow). For larger storms (up to the 100-yr average recurrence interval, ARI), runoff will move through the RSC as both seepage and surface flow. Hydrologic TR-20 modeling of an RSC site receiving runoff from 7.2-ha of low-density residential development in Anne Arundel County, Maryland (MD) showed near-zero surface discharge for the 25-yr ARI (Brown et al., 2010). RSCs in North Carolina perform similarly. An RSC receiving runoff from a 5-ha impervious watershed along Hwy 17

in the Coastal Plain, NC reduced overall surface flow by 98% (Chapter 3). Another RSC receiving runoff from rest stop parking area in the Piedmont, NC achieved overall surface volume reduction of 80% (Chapter 4). Surface volume reductions are predominantly attributed to the conversion of surface flow to subsurface seepage. Water balances from the NC RSCs calculated that between 50% and 100% of surface runoff leaves the RSC as seepage on a storm-by-storm basis (Chapter 3, Chapter 4).

RSCs have shown evidence of providing opportunities for physical pollutant removal (i.e. sedimentation, filtration). Mean effluent TSS concentrations in RSCs in both NC and MD were between 10 and 20 mg/L (Filoso, 2013; Browning, 2008; Chapter 4). The aforementioned NC Piedmont RSC also reduced total phosphorus (TP) by 20%, likely due partitioned phosphate to settleable particles. Pollutant removal mechanisms contributing to these reductions include sedimentation in the pools, and some sand filtration as surface and subsurface flows interchange (Chapter 4).

Other pollutant removal mechanisms, such as biotransformation, appear to depend on RSC conditions. An RSC receiving runoff from a medium-density residential neighborhood in Anne Arundel County was built with a longitudinal slope up to 10%. This RSC remained dry for the majority of the year, except for some seasonal ponding in some of the lowest pools (Filoso, 2013). A nearby RSC receiving runoff from a low-density residential neighborhood, built with a longitudinal slope less than one percent, remains wet throughout the year and has wetland-like conditions across the entire footprint (Browning, 2008). Runoff from the steeper, dryer RSC did not have significantly different concentrations of Nitrite/Nitrate-N (NO_3), Ammonium (TAN), total dissolved nitrogen (TDN), or total nitrogen (TN) concentrations in its surface outflow compared to the neighboring control outfall (Filoso, 2013). On the other had, the flatter, wet RSC, had consistent 20% to 40% NO_3 and TAN reductions from the inflow to the outflow, suggesting that a wetter system may

provide more opportunities for nitrogen biotransformation (i.e. nitrification and denitrification) (Browning, 2008). The Piedmont NC RSC contained a series of pools that remained wet for extended periods of time. This RSC had overall reductions in TN (30%), TKN (37%), and TAN (33%). In contrast to the MD site, these reductions did not occur in the wet areas of the RSC, likely due to a lack of vegetation establishment (Chapter 4). On the other hand, the observed nitrogen reductions suggest the potential for some degree of microbial transformations in well-drained RSCs, as well as wet systems.

Currently, all water quality performance analysis on RSC systems has focused on effluent surface flow. However, as with shallow interflow observed in undeveloped watersheds (Haria and Shand, 2006; Soulsby, 1995; Wenninger et al., 2004), RSC seepage will also contribute to a stream hydrograph. Therefore, pollutant loadings in seepage should be considered when evaluating RSC stormwater mitigation.

Hydrologically, seepage is different from surface flow in that it percolates slowly through the media. The slow moving water contributes to making hydrographs from impervious, undeveloped areas flatter and wider than one from an urban watershed (Brown et al., 1999). Bioretention cells have shown the ability to match this “slow water” pathway as runoff travels through the media – enough to effectively mimic stream hydrographs (DeBusk et al., 2011). Studies have shown that additional pollutant removal mechanisms may be present in shallow interflow pathways, including biotransformation (Cooper, 1990; McDowell et al., 1992; Lowrance et al., 2000; Peterjohn and Correll, 1984), plant uptake (Cooper, 1990), chemical transformations and filtration (Peterjohn and Correll, 1984). However, there has been no investigation as to whether these mechanisms are active within the RSC media, as seepage pollutant concentrations have not yet been measured.

UV-visual spectrometry has been used to measure real time nitrogen species at high frequencies. Spectrometer probes record light attenuation at a range of wavelengths

and convert them to decadal absorption coefficients. A variety of mathematical approaches have been used to correlate pollutant concentrations to the absorption coefficients (Crumpton et al. 1992; Langergraber et al., 2003; Hochedlinger, 2005; Olsen, 2008; Torres and Bertrand-Krajewski, 2008). Partial least square regression (PLSR) approaches have recently provided the most accurate and robust results. Langergraber et al. (2003) calculated a correlation coefficient of 0.68 between NO_3 samples in urban drainage and a PLSR model prediction based on spectrometer wavelength data. Rieger et al. (2006) found only weak correlations to NO_3 samples from wastewater using the same PLSR method, possibly due to interfering absorbance from high turbidity. Until recently, spectrometry has been primarily used to measure NO_3 and organic nitrogen (ON) due to the inherent ability of these species to absorb certain light wavelengths (Crumpton et al., 1992; Olsen, 2008), but there is the possibility that covariance with other nutrient properties may result in correlations between spectrometer readings and other nutrients. Etheridge et al. (2014) was able to find strong spectrometer correlations to NO_3 , TKN, and TP in a tidal marsh in coastal NC. No studies were found correlating light absorbance to total ammonia nitrogen (TAN).

A field-scale RSC was built at the NCSU Lake Wheeler field property in NC. The research site received runoff via storm simulation from a retention pond used to supply water for on-site research. Surface and subsurface monitoring occurred with the intention of

- i. Validating a UV-Vis method for measuring nitrogen concentrations in the media of RSCs,
- ii. Measuring nitrogen fate as runoff enters and drains from the RSC, and
- iii. Estimate nitrogen speciation and loading in RSC seepage.

This research provides a stepping-stone for further research of subsurface dynamics with RSC systems. As RSCs are becoming a popular SCM, subsurface water quality

monitoring is needed to provide a comprehensive investigation into the ability of RSCs to manage stormwater pollutants.

5.3 Methodology

5.3.1 Site Description

An RSC was built at the North Carolina State University Lake Wheeler Road Field Lab (35.72816° N, 78.67981° W) in Fall 2013. The RSC was 38.1 m long with an elevation drop of 0.44 m. It consisted of four pools, 7.6 m long, 6 m wide, separated by three riffles, 2.4 m wide and long (Figure 5-3, Table 5-1). Each riffle had approximately a 4% slope. The sand media bed beneath the system was 0.9 m deep below the riffles and 0.46 m deep below the pools. Pools were 0.46 m deep. A waterproof liner was placed between the hydraulic soil group (HSG) D soils and the sand media to inhibit potential groundwater interchanges. A perforated corrugated drainpipe was placed within the media to allow the system to drain, and simulate seepage observed in previous RSC research (Brown et al., 2010; Chapter 3, Chapter 4). Class 2 rip rap (diameter between 15 cm and 40 cm) was placed as parabolic boulder weirs between the downstream of each riffle and the upstream of each pool. Each riffle was armored with 57 stone (diameter approximately 2 cm). The entire site was hydro-seeded with a stabilization grass mix and covered with 5 cm of triple shredded hardwood mulch.

The RSC was fit with inlet and an outlet weir boxes (Figure 5-4). The outlet weir box was 30.5 cm wide, 91 cm long and 91 cm deep. The box was separated by a 90-degree v-notch baffle wall for measuring surface flow leaving the RSC. The drainpipe was extended through the first compartment of the outlet weir box via 7.6-cm PVC pipe and fitted with a ball valve to control drainage rates. Seepage from the RSC could only enter the second compartment of the weir box. The weir box was drained via a 10.1-cm drainpipe leaving the second compartment of the outlet weir box (Figure 5-4). The inlet weir box received storm-simulated runoff from 20.3-cm

pipe directing water from the retention pond. The weir box had the same exterior dimensions as the outlet weir box. A 61-cm high baffle was placed 30 cm above the bottom of the inlet weir box to maintain head in both compartments of the box, but to avoid the surface turbulence near the 30.5 cm tall 90-degree v-notch directing the storm into the RSC.

Table 5-1 Lake Wheeler RSC design characteristics

	<i>Pool</i>	<i>Riffle</i>
Quantity	4	3
Length	7.6 m	2.4 m
Width	6 m	2.4 m
Surface Area	35.8 m ²	5.8 m ²
Depth	0.46 m	0.15 m
Slope	0%	4.30%
Mulch Depth	5 cm	NA
Cobble Depth	NA	0.15 m
Sand Depth	0.46 m	0.76 m
Available Surface Storage	14.2 m ³	0.7 m ³
Available Subsurface Storage	11.3 m ³	5 m ³

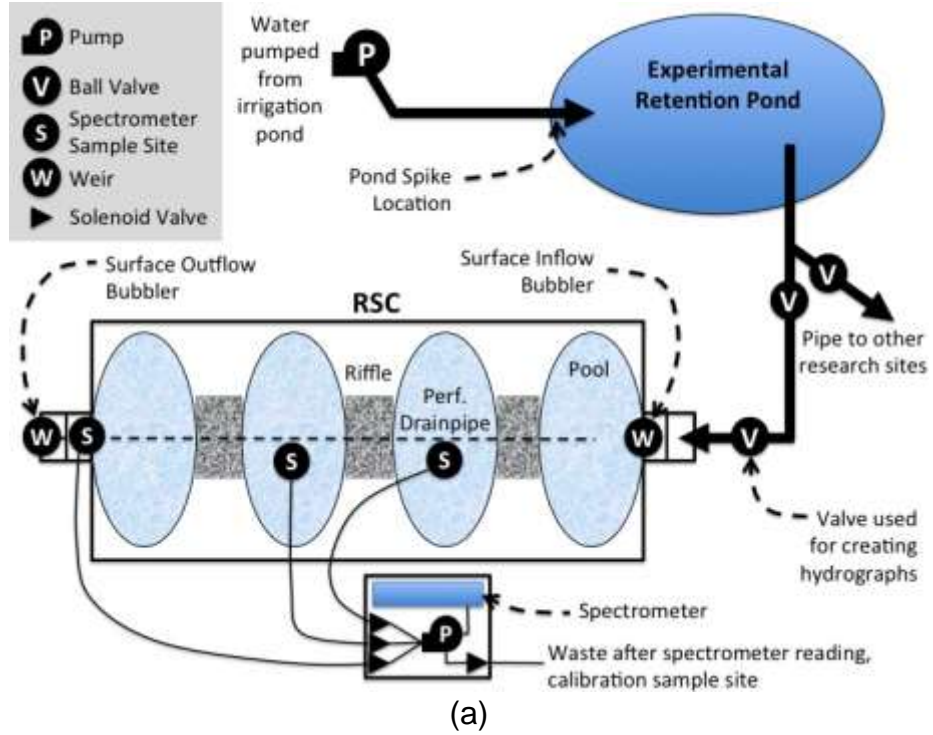


Figure 5-3 RSC Lake Wheeler field site (a) and storm simulation and monitoring layout (b).

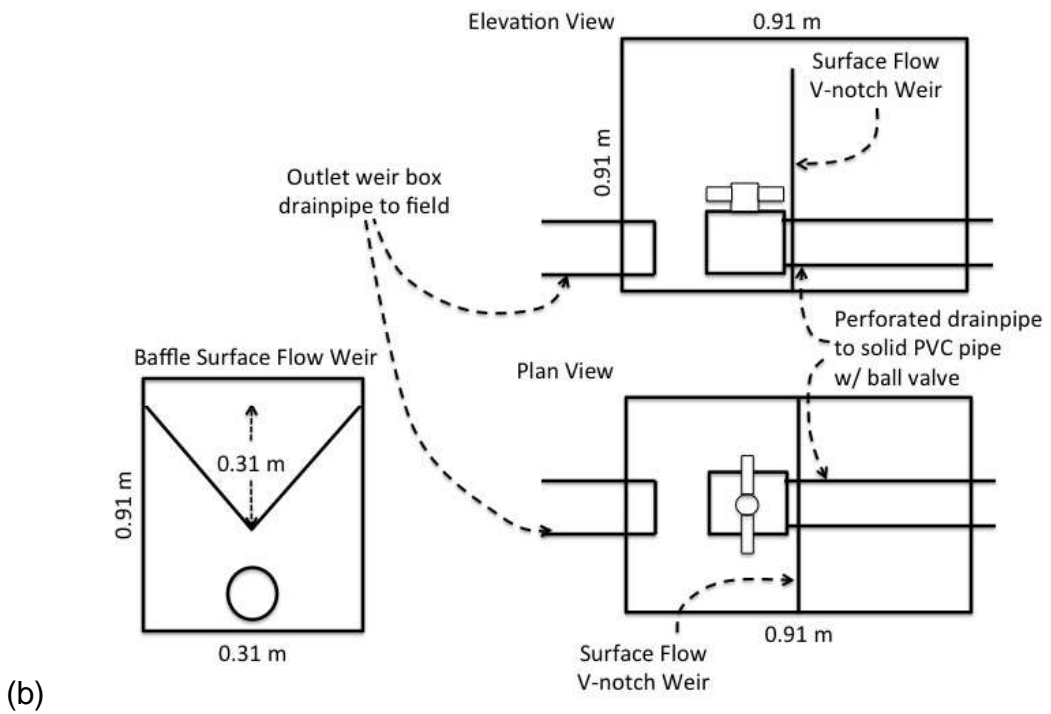
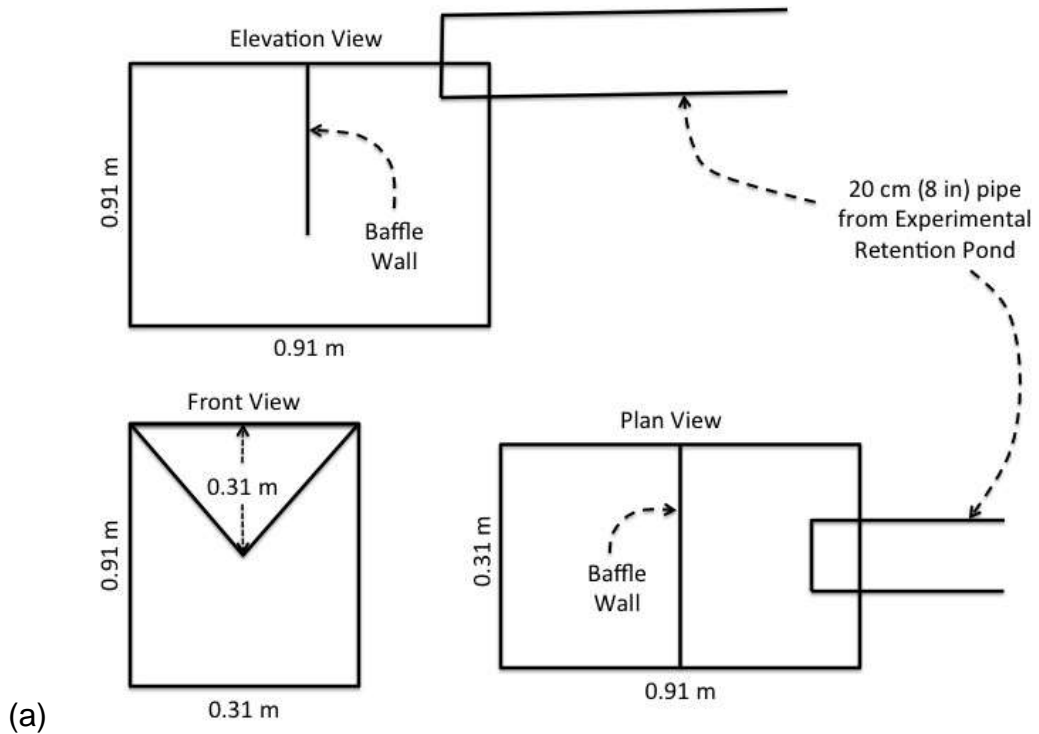


Figure 5-4 Inlet weir box (a) and outlet weir box (b) schematics

5.3.2 Storm Simulation

Nine storms, of three different size events (2-, 10-, and 50-yr, 24-hr average recurrence intervals, ARI), simulated for a 0.1-ha urban watershed in Raleigh, NC were routed through the RSC (Table 5-2). Runoff volumes and flows for each storm event were calculated using the SCS Curve Number Method using a curve number, CN of 77 (SCS, 1985) and the Rational Method using a runoff coefficient, C, of 0.74 (ASCE, 1996), typical of high density watersheds with 30% green space. Given the calculated runoff volume and peak flow, a step-function described in Eq. 1, (Malcom, 1989), was used to estimate the center-weighted hydrograph for each storm event.

$$q_i = \begin{cases} \frac{Q_p}{2} \left[1 - \cos\left(\frac{\pi t_i}{T_p}\right) \right] & \text{for } t_i \leq 1.25T_p \\ 4.34Q_p \exp\left(-1.30 \frac{t_i}{T_p}\right) & \text{for } t_i > 1.25T_p \end{cases} \quad \text{Eq. 1}$$

where q_i is the respective flow rate for time t_i cms

Q_p is peak design flow rate in cms

T_p is the time to Q_p in seconds, calculated by $T_p = \frac{V}{1.39Q_p}$

V is the total runoff volume in m^3

Storms were simulated via a pipe distribution system from the experimental retention pond into the RSC (Figure 5-3). The amount of water entering the inlet weir box, corresponding to the height over the inlet weir, was manually adjusted every 5 minutes using a ball valve located on the 20-cm pipe bringing the water directly to the weir box. The simulated storm, then, differed from the calculated storm in that it was stepped (Figure 5-5), but the volume and peak flows were still representative. The experimental retention pond was fed by pump from an agriculture irrigation pond located on the NCSU Lake Wheeler Field Lab property. The experimental retention

pond held approximately 190,000 L of water. Per previous storm simulations by Davis et al. (2006), the pond water was spiked at the feed (Figure 5-2) with glycine and sodium nitrate to achieve 4 mg/L TKN-N and 0.4 mg/L NO₃-N, respectively.

Table 5-2 Simulated storm hydrograph information including precipitation, intensity, runoff volume, and peak flow rate

	<i>2-yr</i>		<i>10-yr</i>		<i>50-yr</i>	
Precipitation (cm)	8.7		12.9		17.1	
Intensity (cm/hr)	14.4		18.4		21.7	
Runoff Volume (m ³)	32.3		64.8		100.5	
Peak Flow Rate (L/s)	30.0		38.4		45.3	
<i>Simulated Hydrograph Flows and Water Levels</i>						
Tim (min)	Avg. Flow (L/s)	Water Level (cm)	Avg. Flow (L/s)	Water Level (cm)	Avg. Flow (L/s)	Water Level (cm)
5	3.9	9.5	2.2	7.5	1.5	6.4
10	18.5	17.8	12.5	15.2	9.1	13.3
15	28.9	21.3	26.7	20.6	21.2	18.8
20	22.6	19.3	36.6	23.4	33.9	22.7
25	13.7	15.8	36.5	23.4	42.7	24.9
30	8.3	12.9	28.1	21.0	44.8	25.4
35	5.0	10.5	20.4	18.5	39.4	24.1
40	3.0	8.6	14.8	16.2	31.1	21.9
45	1.8	7.0	10.7	14.3	24.4	19.9
50			7.8	12.5	19.1	18.0
55			5.6	11.0	15.0	16.3
60			4.1	9.7	11.7	14.8
65					9.2	13.4
70					7.2	12.1
75					5.6	11.0
80					4.4	10.0

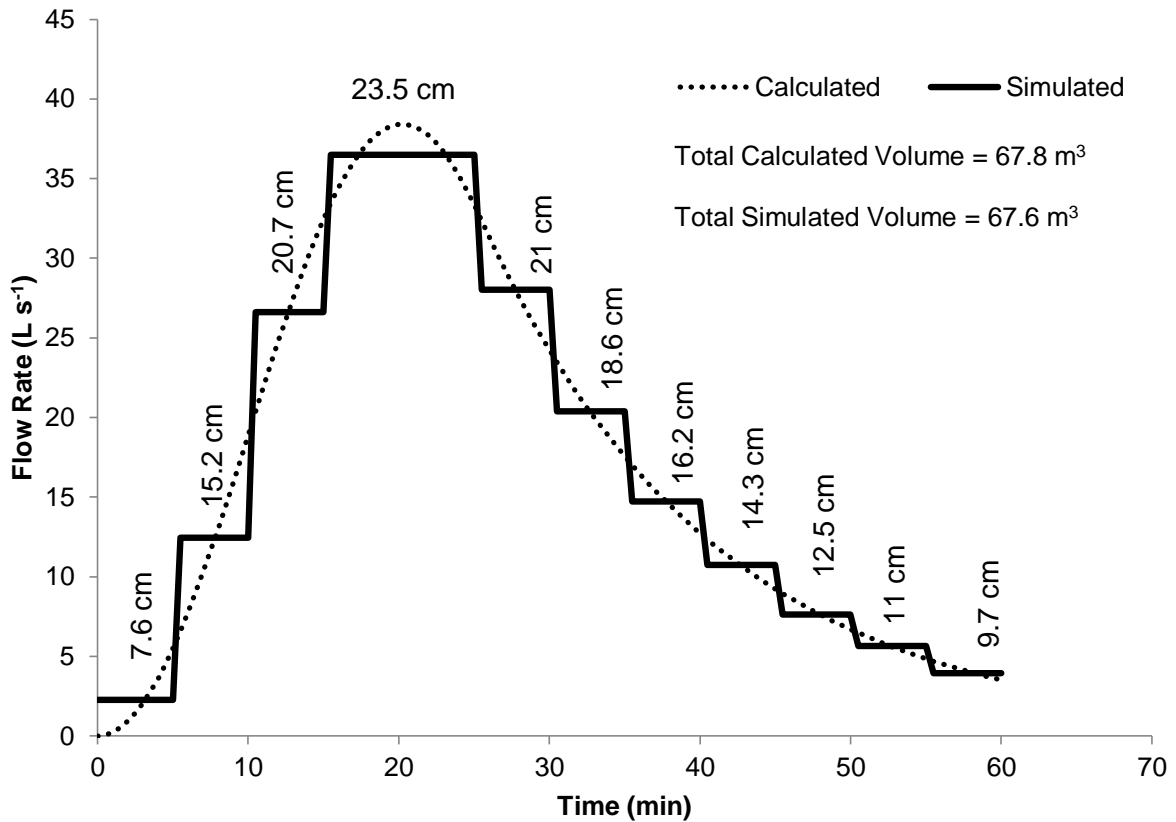


Figure 5-5 Calculated and simulated 10-yr ARI hydrograph. Numbers indicate corresponding water level over the 90° v-notch weir.

At the beginning of a storm simulation, the under drain valve was shut off to allow runoff to infiltrate and the RSC to become saturated by preventing preferential flow through the drainpipe. During this time, water would only leave the RSC as surface flow, mimicking the “quick flow” portion of a hydrograph (Cizek and Hunt, 2013). The site was monitored this way for 8 hours, then the drainpipe ball valve was partially opened to allow treated runoff to seepage from the system until the system was drained, mimicking the “slow flow” portion of the hydrograph. Subsurface monitoring continued during this draining period for 24 hours. In this way, the Lake Wheeler RSC system was considered a well-drained system, without wetland-like conditions (Chapter 4).

5.3.3 Monitoring Setup

Freestanding ISCO 4230 bubblers were used to measure water stage over the v-notch weirs in both the inlet and the outlet weir boxes. During a storm simulation, inlet and outlet surface flow grab samples by hand. Five grab samples were taken disturbed equally by flow over the inlet hydrograph (Table 5-2). Up to three outlet samples were taken approximately distributed across the outflow duration.

Three sampling wells were placed in the RSC for subsurface water quality sampling. The first pool within an RSC acts similarly to a forebay (Chapter 4), the wells were placed in the second pool, third pool, and the drain outlet. Instantaneous subsurface water quality readings were made using a multiplexing pump system and a spectro::lyser UV-Visual spectrometers with a 4 mm measurement path (from s::can Measuring Systems). The spectrometer measured light absorbance at wavelengths between 220.0 nm and 742.5 nm, at 2.5 nm intervals. Sample tubing ran from the bottom of each well through its own solenoid valve and into the spectrometer. The water was then pumped out through a waste tube. The entire pump-measure-waste cycle for each well was 5 min, so water quality readings were taken every 15 minutes for each sampling point. Three calibration samples were taken at each sampling point for each storm using the waste tube. Grab samples and calibration samples were immediately placed on ice and taken to the NCSU Center for Applied Aquatic Ecology to undergo analysis for nitrite/nitrate (NO₃), total kjeldahl nitrogen (TKN), and total ammonium nitrate (TAN).

5.3.4 Partial Least Squares Regression Model

Partial least squares regression (PLSR), described by Langergraber et al. (2003), Torres and Bertrand-Krajewski (2008), and Etheridge et al. (2014) was used to find a model to best predict nitrogen concentration using the absorbance coefficients provided by the spectrometer. PLSR models are widely used in spectrometric and chemotographic application (Torres-Bertrand-Krajewski, 2008). It is a step-wise approach that reduces the dimension of absorption spectra measurements from the

original 210 to a smaller number of components that have the maximal correlation with the nutrient calibration samples. PLSR was performed using the “pls” package (Mevik et al., 2011) in software R. Model training and validation was performed using 20-fold cross validation, where 10% of the calibration data were randomly withheld from the training set, and then used in the model validation. Initial model error during cross validation was calculated using the root mean square error of prediction (RMSEP). The number of components ultimately chosen for a model was determined based on minimizing the RMSEP. PLSR models were calculated for the raw spectra and the first derivative of the raw spectra for each nitrogen species – NO₃, TKN, and TAN. Model goodness of fit was determined with the Nash-Sutcliffe model efficiency test (Eq. 2),

$$NSE = 1 - \frac{\sum_{n=1}^N (C_{o,n} - C_{m,n})^2}{\sum_{n=1}^N (C_{o,n} - \bar{C}_o)^2} \quad \text{Eq.2}$$

where $C_{o,n}$ is observed concentration for data point n

$C_{m,n}$ is the modeled concentration for data point n

\bar{C}_o is the mean of the observed concentrations

N is the total number of data points

such that for NSE values of 0.900 to 1.000, the model is a very good fit; for 0.800 to 0.900, the model is a good fit; for 0.650 to 0.800, the model is acceptable; and for NSE values less than 0.650, the model is unsatisfactory.

5.3.5 Statistical Analysis

The final PLSR model for each pollutant was applied to the entire dataset to find nitrogen concentrations at 15-minute intervals. These datasets were tested for normalcy using the Shapiro-Wilk test and visual assessment. The data were uniformly non-normal; therefore, non-parametric statistical methods were used to further analyze the data. Inflow and seepage concentration differences, as well as

initial seepage verses final seepage concentrations were tested for significance using the Wilcoxon Rank-Sum Test. Bi-hourly seepage data were also tested for ordered significance using the Jonckheere-Terpstra test, which would indicate progressive pollutant reductions over time (i.e. conc. at hr 2 > conc. at hr 4 > ... > conc. at hr 12). For all statical analysis, the data was significant when Type I error (α) was less than 0.05.

5.4 Results

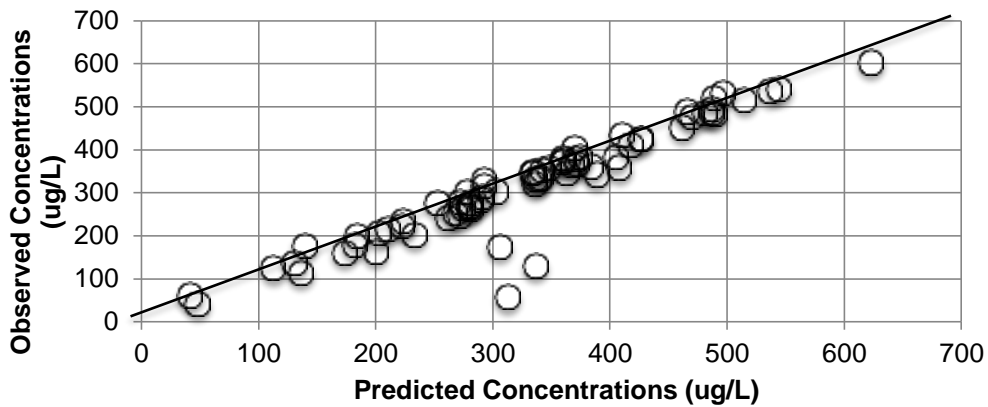
5.4.1 Partial Least Squares Regression Model Calibration

During the nine simulated storm events, 81 calibration samples were taken. Spectrometer readings for the first storm simulated did not match up with calibrated samples due to a pump timing failure. Therefore, the remaining 72 samples were used to train and validate the PLSR models. The RMSEP for different component quantities were heavily influenced by which calibration points were randomly chosen to validate the model. Therefore, the model was run ten times and the median RMSEP were plotted. Then component quantities associated with dips in the median RMSEP were used in the PLSR model to predict pollutant concentrations using the spectrometer measurements. Well- to very well-correlated PLSR models were found for NO₃ concentrations using the raw spectra with fifteen components (NSE = 0.87) and for TKN using the raw spectra with nineteen components (NSE = 0.997) (Table 5-3, Figure 5-6). It makes sense that relatively strong correlations were found because both nitrate and organic matter have some absorbency potential (Crumpton et al., 1992; Olsen, 2008), and strong correlations have been found for these nitrogen species in the past (Etheridge et al., 2014). Furthermore, as samples have been filtered via the RSC sand-media, interfering TSS concentrations would be quite low. Despite trying several different TAN models, there did not appear to be a significant correlation between spectrometer measurements at any range of wavelengths and TAN concentrations. However, marginally better results were observed using the first derivative of the raw spectra than the raw spectra, or $d\lambda/dA$,

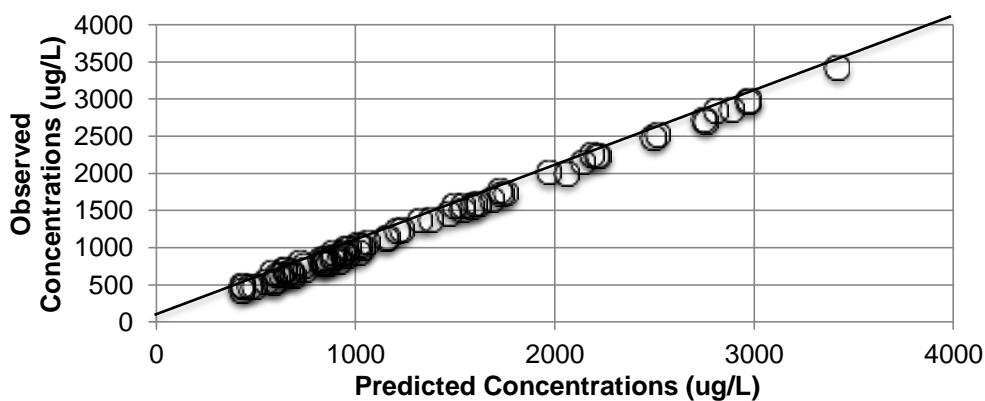
where λ is wavelength A is the measured absorbance (NSE = 0.11 for raw spectra
 verse NSE = 0.23 for first derivative of the raw spectra).

Table 5-3 PLSR models and components tested with Nash-Sutcliff goodness of fit
 test

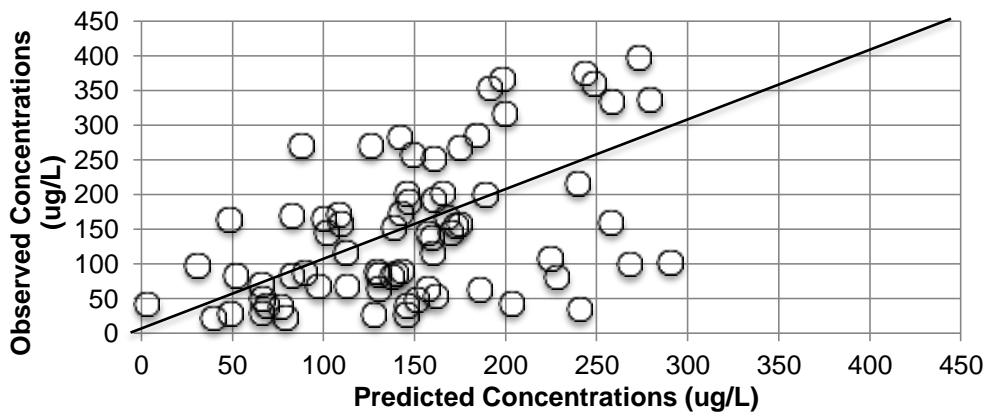
Pollutant	Spectra	# of Components	NSE
NO3	raw	8	0.70
	raw	15	0.87
	1st derivative	3	0.54
	1st derivative	9	0.81
	1st derivative	10	0.82
TKN	raw	2	0.10
	raw	8	0.77
	raw	9	0.86
	raw	19	0.997
	1st derivative	1	0.10
	1st derivative	4	0.71
	1st derivative	9	0.82
TAN	raw	3	0.11
	raw	4	0.11
	raw	5	0.14
	1st derivative	3	0.23



(a) NO₃, using the raw spectra with 15 components



(b) TKN, using the raw spectra with 19 components



(c) TAN, using the 1st derivative of the raw spectra with 3 components

Figure 5-6 Optimal PLSR model predicted NO₃ (a), TKN (b), and TAN (c) concentrations compared to observed concentrations.

5.4.2 Surface Flow

The simulations in the RSC resulted in outflow during the 10-yr and 50-yr ARI storm events. Approximately 15 min of slow surface discharge (peak flow ~ 0.5 L/s) did occur during the third 2-yr storm event storm simulation. Exact discharges are unknowns, as significant data loss from the surface monitoring equipment (due to a combination of multiple periods of sub-freezing temperatures and programming issues) rendered inlet and outlet flow data unusable. For the remainder of the paper, inflow hydrology is assumed to match the simulated hydrograph for each of the events, as water levels over the weir were regulated every 5-min. The RSC was able to flatten the peak and extend the outflow period relative to the short, spiky inflow hydrograph. Inflows into the system occurred for time periods between 45 minutes and 90 minutes. Surface outflow for these same events were small relative to inflows, with peak flows equal to approximately 30 L/s, and occurred (and sampled) over a several hour period.

Inflow nitrogen concentrations were more variable than expected (Table 5-4). The pond was spiked using the powder form of the synthetic pollutants, and it appears that adequate mixing was not provided at the feed pipe to allow for the chemicals to fully dissolve before settling to the bottom of the pond. Higher concentrations of both NO₃ and TKN appear when the spiked pond stage is lowest (1/21/14 and 2/7/14). Nevertheless, all the concentrations are reasonable concentrations for urban runoff (0.2 to 1.0 mg/L NO₃, 1.5 to 3.0 mg/L TKN) (US EPA, 1983; Passeport et al., 2009). Outflow concentrations for each of the nitrogen species were not significantly different from the inflow concentrations, meaning that there were very few nitrogen removing mechanisms occurring through the surface flow pathway in the RSC (Table 5-4). This is consistent with surface flow performance in the well-drained Anne Arundel County RSC (Filoso, 2013), and confirms the need for further removal mechanisms in the subsurface of the RSC to reduce overall RSC nitrogen loadings to surface water.

Table 5-4 Inflow and outflow surface, and hourly subsurface median well concentrations. Bold values indicate significant difference from the inflow concentration.

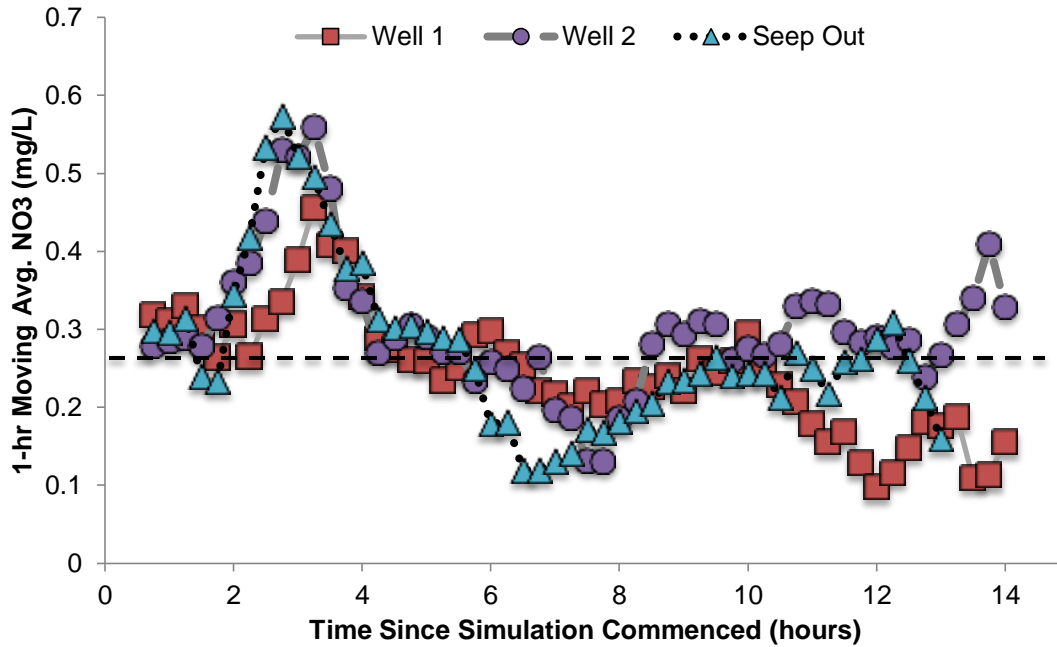
	Inflow	Outflow	Hr 1	Hr 2	Hr 3	Hr 4	Hr 5	Hr 6	Hr 7	Hr 8	Hr 9	Hr 10	Hr 11	Hr 12	Hr 13	Hr 14
<i>NO3 (mg/L)</i>																
Well 1	0.38	0.38	0.33	0.31	0.32	0.36	0.29	0.29	0.31	0.26	0.31	0.26	0.28	0.25	0.25	0.27
Well 2	0.38	0.38	0.33	0.31	0.41	0.36	0.31	0.26	0.29	0.31	0.28	0.26	0.28	0.29	0.27	0.25
Seepage	0.38	0.38	0.29	0.32	0.37	0.35	0.33	0.33	0.34	0.30	0.26	0.27	0.31	0.28	0.25	0.30
<i>TKN (mg/L)</i>																
Well 1	1.41	1.68	1.40	1.43	1.24	1.15	1.29	1.20	1.06	1.01	1.19	1.38	1.09	0.93	0.94	1.00
Well 2	1.41	1.68	1.69	1.41	1.18	1.48	1.03	1.20	1.07	1.32	1.15	1.07	0.93	0.71	1.03	1.13
Seepage	1.41	1.68	1.32	1.35	1.23	1.22	1.25	1.14	1.31	1.05	1.18	1.10	1.13	1.10	1.39	1.22

5.4.2 Subsurface Flow

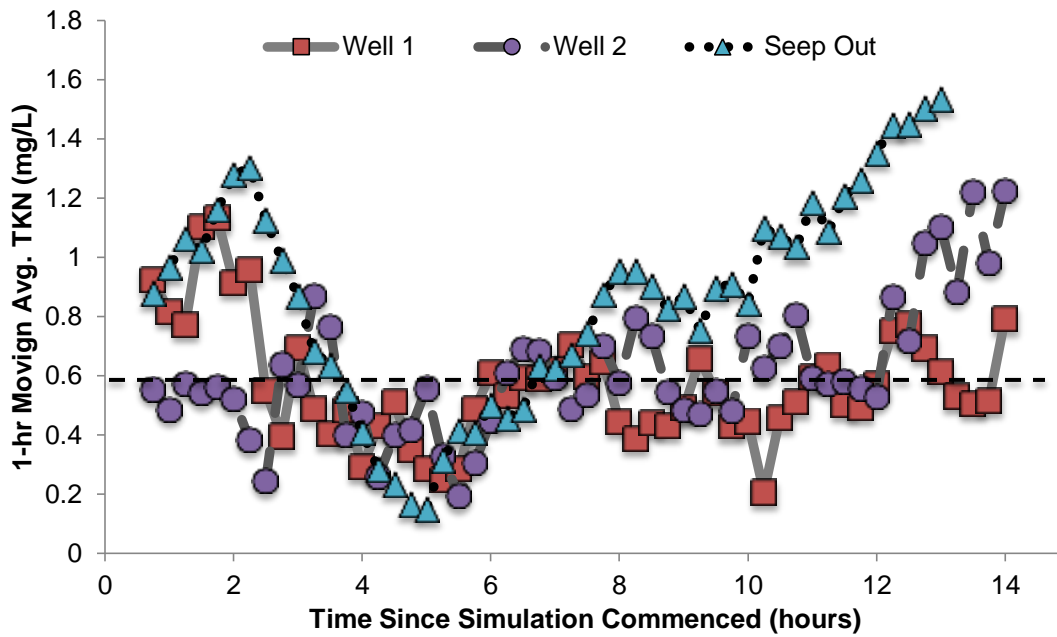
Nitrogen concentrations in the subsurface wells varied somewhat from storm to storm. The first two storm simulations (1-15-14 and 1-17-14) experienced spikes in NO₃ and TKN subsurface flow concentrations beyond surface inflow levels (Figure 5-7). These peaks were only observed during the initial two events, suggesting a probable flushing phenomenon. Flow simulations were run through the RSC prior to monitoring commencement, but none of these runs resulted in subsurface saturation, as the drainpipe valve remained open. Then, media saturation during the monitored simulations likely resulted in initial nitrogen flushing from the media. After the first two monitored simulations, subsurface nitrogen concentrations were reduced as described in Table 5-4. Significant reductions between nitrogen inflow concentrations and average hourly well concentration began at hour 6, and, for the most part, continued through hour 10, and in some cases, up through hour 14 (Table 5-4). For most storms, wells became unsampleable due to low flows by hour 14. Overall, at hour 10, median NO₃ and TKN reductions, relative to surface inflows, were 30% and 20%, respectively.

Nitrogen concentrations were tested to determine if there was progressive treatment over time within the RSC media. Progressive reductions in subsurface TKN concentrations were significant over time from a median concentration of 1.35 mg/L at hour 2 to 1.11 at hour 12 (p-value = 0.041) (Table 5-4). Subsurface NO₃ showed similar significant progression if allowable Type I error was increased to $\alpha=0.10$. This progression of nitrogen reduction also suggests removal via microbial processes, which require time, versus physical processes, where reductions would appear immediately as water has been filtered. It is important to note that air temperatures during the monitoring period varied from 0.2° C to 16.4° C when wells within the RSC media were sampled. Soil temperatures at the Lake Wheeler property (NC State Climate Office, site LAKE in Raleigh, NC) were measured between 3.6° C and 10.6° C. Both nitrifying and denitrifying bacteria have shown some activity when soil

temperatures are between 5° C and 10° C in treatment wetlands (Kadlec and Reddy, 2001). It may be that some denitrification is occurring during periods of the higher temperatures, thus resulting in the NO₃ reductions observed. These reductions, therefore, are likely to increase with increasing temperatures (Kadlec and Reddy, 2001).



(a) NO3



(b) TKN

Figure 5-7 NO3 (a), TKN (b), and TAN (c) subsurface concentrations during the 2-yr storm simulated on January 15, 2014. Notice initial pollutant peaks for all pollutants. Dashed line indicates surface inflow concentration.

5.4.3 Estimated Subsurface Loading Contribution

Water balance calculations on RSCs in North Carolina have shown that between 50% and 100% (median 80%) of runoff leaves the system as seepage, depending on the storm size (Chapter 3, Chapter 4). Lake Wheeler RSC surface outflow and Hr 10 seepage concentrations from Table 5-4 were multiplied by surface and seepage volumes estimated by these different hydrologic scenarios to estimate nitrogen loading to receiving waters (Table 5-5). The RSC test site showed some reduction in nitrogen species through the media bed, but that these pollutants are ultimately present in the seepage. Under the winter-time Lake Wheeler RSC conditions, nitrogen loadings from the seepage were even greater than those contributed by surface loadings for most storms (Table 5-5). It is important to note, however, that as runoff converted to seepage, the overall nitrogen loadings coming from the RSC decline. Thus, in addition to the hydrologic benefits, the conversion of surface flows to seepage is very important to RSC water quality performance, but still needs to be considered as a pollutant contributing pathway to surface waters. Further research should be conducted to examine RSCs exhibiting wetland-like conditions (Chapter 3, Chapter 4) and nitrogen reductions during warmer weather events to provide accurate annual seepage loadings.

Table 5-5 Calculated surface and subsurface pollutant loadings for a range of observed flow scenarios

		2-yr (g/storm)			10-yr (g/storm)			50-yr (g/storm)		
		50% Seep	80% Seep	100% Seep	50% Seep	80% Seep	100% Seep	50% Seep	80% Seep	100% Seep
Surf	NO3	6.17	2.47	0.00	12.37	4.95	0.00	19.18	7.67	0.00
	TKN	27.23	10.89	0.00	54.53	21.81	0.00	84.57	33.83	0.00
Seep	NO3	4.58	7.32	9.15	9.17	14.67	18.33	14.22	22.75	28.44
	TKN	17.87	28.59	35.73	35.78	57.25	71.56	55.50	88.79	110.9 g
Total	NO3	10.75	9.79	9.15	21.53	19.61	18.33	33.40	30.42	28.44
	TKN	45.09	39.48	35.73	90.31	79.06	71.56	140.1	122.6	111.0

5.5 Discussion

Up to this point, research on RSC performance has focused on surface flow hydrology and water quality (Browning et al., 2008, Brown et al., 2010, Filoso, 2013, Chapter 3, Chapter 4). This research confirms the need for further study on seepage from RSCs as a potential source of stormwater pollutant loads into water bodies. This research also lays out an effective methodology for rigorous subsurface water quality analysis. At field sites, automated grab samplers are often triggered by water elevation, unless manually triggered prior to a storm event. As subsurface water elevations vary from storm to storm, and may remain elevated for extended amounts of time, grab samples are manually more intensive to acquire and process. Additionally, as subsurface drainage can be slow, with potential microbial processes occurring over several days, the number of grab samples required to document subsurface water quality changes would be expensive to analyze. The spectrometer with multiplexer pump setup is an accurate and inexpensive method for measuring NO₃, TKN, and total nitrogen (TN) concentrations at higher frequencies over extended amounts of time. Previous work in surface waters and urban drainage systems show that this same apparatus may also be used for measuring total suspended solids (TSS), total phosphorus (TP), and possibly even ortho-phosphate (OP) (Langergraber et al., 2003; Hochedlinger, 2005; Rieger et al., 2006; Torres and Bertrand-Krajewski, 2008; Etheridge et al., 2014.). This paper offers a methodology to monitor such pollutants in RSC subsurface flow.

The measured nutrient reductions in the seepage, albeit small, were both surprising and encouraging to see in the well-drained RSC during such cool temperatures, as the RSC was tested during a season of slow microbial activity due to temperature (Mulholland, 1992) . The concentration reduction over the course of 12 hours suggests several possible pollutant removal mechanisms. First, runoff initially entering the sampling well is through upper well perforations and has only undergone a few centimeters of media filtration. As the water drains further into the

media, TKN ions with some affinity for charged soil and carbon particles, may be removed via adsorption and filtration (Jellali et al., 2010). However, significant TKN and nitrate reductions via microbial processes have been observed in slow sand filters treating municipal wastewater when water temperatures were as low as 10° C (Nakhla and Farooq, 2003). This suggests that some removal, particularly of NO₃-N is due to biotransformation, namely denitrification. Despite the fact that the RSC became unsampleable within 14 hours, there is still approximately 35% by volume of the water still present in the media after 24 hours of draining and 16% present 48 hours after draining, as determined by water retention tests on the Lake Wheeler subsurface media. This results in approximately 18 m³ of runoff remaining in the system 48 hours after draining to undergo further microbial treatment. If this water then contributes to seepage in subsequent storm events, there could be a dilution effect of up to 56% for the 2-yr storm event or 18% for the 100-yr storm event. Ultimately, microbial processes appear to be the main nitrogen pollutant removal mechanism in the subsurface of RSCs, and performance is likely to increase with increasing temperatures (Kadlec and Reddy, 2001).

As microbial transformations are critical to reducing nitrogen loading from RSC seepage, it is important to consider what RSC design characteristics may be important to optimize contact of pollutants in runoff and a vibrant microbial environment. Mixing organics into the media (in this case, 20% to 30% woodchips by volume, and a thick layer of shredded mulch on the surface) appear to contribute to initial nitrogen flushing from the system; although, in this case, does not appear to be a continued problem. The organic matter, particularly the carbon, is necessary for establishing both vegetation and a microbial community (Chen et al., 2003). Additionally, media-based SCMs that have alternating wet and dry conditions appear to enhance nitrogen removal by providing environments for both nitrification (aerobic) and de-nitrification (anaerobic) (Brown and Hunt, 2011). Despite some apparent nitrogen removal in dry systems, it is conceivable that RSCs with saturated

zones may perform similarly to bioretention with internal water storage (IWS), achieving higher mean TKN and NO₃ reductions of 88% and 45%, respectively (Brown and Hunt, 2011). Some RSCs in NC and MD have wet zones resulting from raised water table elevations such that they become seasonally saturated pools (Browning et al., 2008; Chapter 3). Another RSC in the Piedmont of NC created a saturated zone by providing exfiltration trenches in the bottom of the media such that the bottom of the media mirrored the pool riffle elevation on the surface (Chapter 4). Currently, RSC design guidance does not include or benefit engineers for creating saturated zones (Anne Arundel County Department of Public Works, 2012; MD Department of the Environment, 2014). It is the recommendation of these authors to provide incentive for creating some saturated zones within RSCs.

5.6 Conclusion

RSCs are a popular SCM in the Eastern United States, with new systems being installed annually in Maryland, North Carolina, and Washington, D.C. However, field performance of RSC has not been extensively researched. The limited research available focuses on the ability of RSC to reduce surface flow and associated pollutants. As these systems function by converting surface flow to subsurface flows, it is critical to evaluate potential pollutant loadings leaving RSCs via seepage. This research provides a methodology for accurately and inexpensively monitoring subsurface nitrogen concentrations at high frequency for extended periods of time, with the possibility of extending monitoring to include TSS and phosphorus species. This research also supports the theory that nitrogen loadings exist in the seepage and should be further researched and quantified. It is likely that RSCs have the ability to mitigate nitrogen pollution via subsurface pollutant removal mechanisms, however, optimal design characteristics, namely both unsaturated and saturated zones, should be present within the media bed. As more and more RSCs are installed, particularly in nutrient sensitive waters, it is essential that further research

both support and guide engineers and regulators in fully understanding RSC performance as SCMs.

5.7 Acknowledgements

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6. Quantification of Select Ecosystem Service Indicators Provided by RSC in Maryland and North Carolina

6.1 Abstract

Regenerative stormwater conveyance (RSC) systems are open channel, sand filtering systems that utilize a series of shallow aquatic pools, riffle and weir grade controls, native vegetation, and underlying sand channels to treat, safely attenuate, and convey storm flow. RSCs have demonstrated the ability to treat and manage stormwater runoff. Also, per their nature-based design, they have a high potential to offer additional ecosystem services, including climate regulations, habitat provision, and nutrient cycling. As RSCs are often located in close proximity to developed areas, such ecosystem services can be directly realized by surrounding communities. A chronosequence of 14 sites varying from 1 to 14 years old were assessed for the presence and extent of select ecosystem service indicators. Soil carbon accumulation, microbial biomass carbon, and habitat provision significantly increased as RSCs established over time. Annual carbon accumulation was measured at 2.15 g C per kg soil. Correlations between age and areal carbon density were strongest when comparing well-drained or seasonally-ponded RSC only. Microbial biomass carbon density was similar to reference sites after 5 years of establishment. Biodiversity and cultural benefits are most evident in RSCs when recreational and educational infrastructure, plantings, and wet areas are incorporated into RSC design. Possible confounding factors to habitat, cultural benefits, and carbon accumulation include RSC hydrology and watershed imperviousness. Overall, ecosystem services provided by RSC are similar to or exceed those demonstrated in constructed stormwater wetlands in all aspects except cultural benefits. The select indicators suggest that ecosystem services are valued up to \$67,300 ha⁻¹ for the first 15 years of RSC establishment.

6.2 Introduction

Human populations derive essential benefits, both directly and indirectly, from the natural ecosystems around them. These benefits, referred to as *ecosystem services*, substantially influence all components of human wellbeing, including basic material needs, health, good social relations, and security (MEA 2005a). Ecosystem services come in the form of provisioning, regulating, and cultural, with supporting services (Figure 6-1). Biodiversity is both an effect of healthy ecosystem function and a service in itself, as it underpins the provision of many other services (de Groot, 2006). Aquatic ecosystems, such as wetlands and streams, are especially important to human wellbeing. However, many of these systems are being lost or compromised by urbanization. This problem is likely to continue as more than 60% of the world's population is expected to live in cities by 2030 (UN 2005).

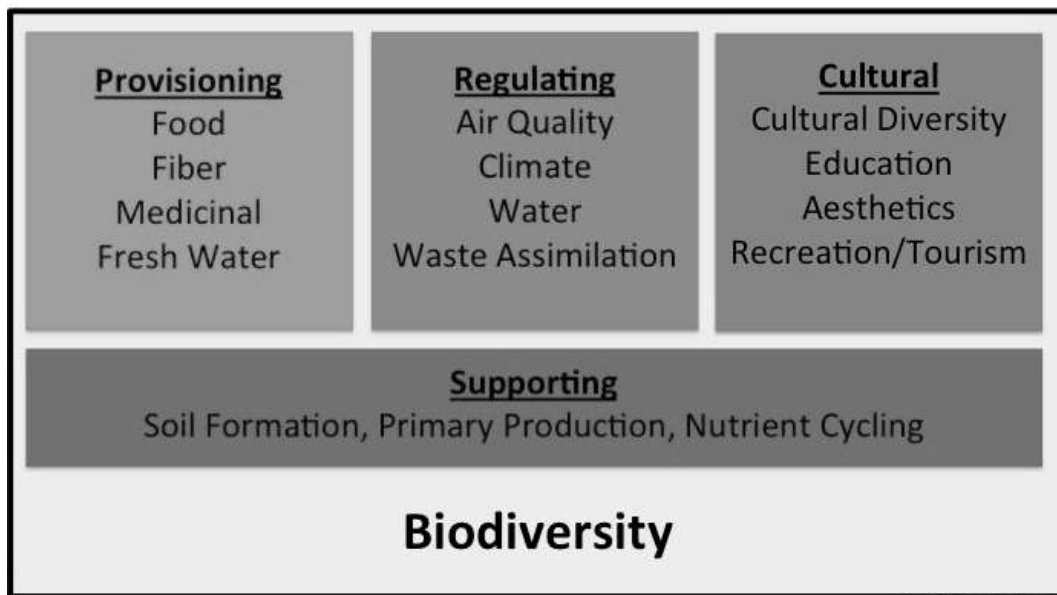


Figure 6-1 Ecosystem services categories and examples

Most land is valued by its potential market value. More recently, efforts have gone into estimating non-market values to ecosystems. In many cases, the non-market services are estimated to be more valuable than market value (MEA 2005a). Costanza et al. (1997) estimated the value of global ecosystem services to be \$33 trillion annually. This value would have to be off by a factor greater than 100 for ecosystem conservation, preservation, and restoration not to make economic sense (Balmford et al. 2002). Loomis et al. (2000) performed a willingness to pay survey of neighborhood residents for restoring a segment of a river in an impaired river basin which would increase water quality, provide erosion control and wildlife habitat, and improve recreation. The survey found the ecosystem services were valued by the neighborhood residents to be \$19 million to \$70 million annually; the lower value was greater than the suggested costs of improving the stream segment. Therefore, land use decisions can be better guided when considering their effects on ecosystem value (often not considered at all).

Ecosystem services are often only considered present in natural ecosystems, but some services are likely to also establish in restored or engineered ecosystems (such as stormwater control measures, or SCMs), although to what extent is unclear. Costanza and Daly (1992) suggest that an ecosystem must have a minimum level of ecosystem infrastructure to allow production of the total range of services. Studies on wetland restoration show that certain ecosystem infrastructure established earlier and more fully than others (Craft et al. 2002; Craft et al. 1988; Craft et al. 2003; Craft et al. 1999). Physical processes related to hydrology were established in first five years. These studies showed that primary production and biological processes strongly linked to primary production, as measured in biomass production and invertebrate populations, became similar to those of the natural marshes in years three to 15. Finally, soil structure and composition similar to natural mashers was observed as soon as 15 years, but often not at all. Studies on other wetland systems have shown similar results. In a study by Zedler (1993), planted cordgrass marshes,

restored to provide habitat for the endangered light-footed clapper rail, were unsuccessful in providing long enough grass stems required for the bird's nesting practices. Thus, even when biomass density appears similar in an engineered system, similar plant quality and diversity may be more difficult to establish. In contrast, an evaluation of an eleven-year old reclaimed riverine forest in Florida showed plant species and soil horizons largely similar to those in a nearby reference site (Clewell, 1999). So it remains unclear as to how engineered ecosystems, such as nature-based SCMs, may provide the ecosystem infrastructure and function needed to ultimately provide important services in urban and suburban areas.

SCMs, including constructed stormwater wetlands (CSW) and stormwater wet ponds (SWP) may offer a suite of additional ecosystem services, as indicated by specific measures of ecosystem infrastructure and function, (i.e. ecosystem service indicators). Moore and Hunt (2012) found CSWs and SWPs across North Carolina (NC) to provide some level of water treatment, hydrologic regulation, carbon sequestration, biodiversity, and educational opportunities. CSWs often outperformed SWPs in provision of ecosystem service indicators, likely due to the varying aquatic environments (i.e. deep pools and littoral shelves) and abundance of vegetation. These SCMs also demonstrated soil carbon accumulation over time, although not to the extent measured in natural reference wetlands. Bishop et al. (2000a) studied wildlife communities in 15 stormwater SWPs aged 3 to 22 years in the Toronto, Canada, region. Species richness of the ponds was low to moderate, indicating that SWPs do not provide a high quality habitat for wildlife. Taxa found in sweep net samples did correlate positively with the age of the pond; however, they also correlated negatively with oil and grease concentrations in the sediment, which is very characteristic of urban SCMs. Additionally, some of the wildlife present at the ponds, namely redwing blackbird eggs, contained detectable levels of pp'DDE and PCB's. There was also statistically lower hatching success of frogs, and larvae took longer to metamorphose in some SWPs than in natural habitats (Bishop et al.

2000b). This research needs to be extended to other SCMs to help guide designers, planners, and regulators desiring to increase ecosystem benefits in the limited available space of urban and suburban areas.

A promising, nature-based SCM called regenerative stormwater conveyance (RSC) is currently being installed across the mid-Atlantic coast (MD Department of the Environment, 2014). RSCs are open channel systems consisting of a porous media bed with a series of riffle/weir step pools (Figure 6-2). Similar to other media-based SCMs, the bed material has a high hydrologic conductivity to promote infiltration into the RSC media. Unlike bioretention media (Hunt et al., 2012), RSC media includes 20% to 30% shredded hardwood trees to serve as a carbon source for nutrient transformations (Anne Arundel County Department of Public Works, 2012). The riffle/pool geometry absorbs energy and retains water by promoting ponding water in shallow pools and slowing water to non-erosive flow velocities. A native plant community may also increase both water quality and hydrologic benefits through plant uptake and evapotranspiration. RSC reduce surface flows by converting surface flows into shallow seepage through the sand media (Brown et al., 2010; Chapter 3, Chapter 4, Chapter 5), thus matching storm hydrographs from similar undeveloped watersheds. These systems are also able to reduce total suspended solids, phosphorus, and, when vegetated wetland-like conditions are present, nitrogen (Browning, 2008; Filoso, 2013; Chapter 4). In addition to stormwater mitigation benefits, Underwood et al. (2005) reported success in planting a flat, wet RSC system (previously referred to as sand seepage wetland in Maryland) to create a thriving Atlantic White Cedar habitat. Thus, in addition to hydrologic and water quality mitigation (regulating services), RSCs have the potential to provide other essential ecosystem services much needed in urban and suburban areas. However, no research has ever quantified these additional benefits.

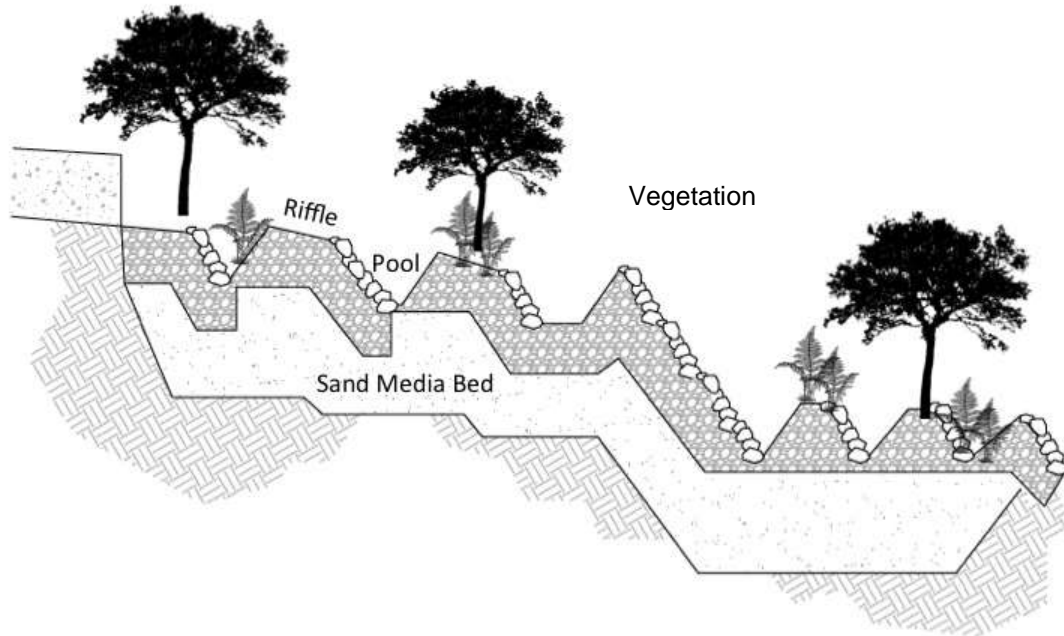


Figure 6-2 RSC profile (typ.), including major design features such as riffles and pools, sand media bed, and native vegetation

The apparent advantage of a nature-based SCM is that, in addition to the designed services of water treatment and flow mitigation, the systems offer additional services generally attributed to healthy ecosystems. It is expected that RSC will offer some degree of opportunity for climate regulation (indicated by soil carbon accumulation), biodiversity (indicated by plant diversity), nutrient cycling (indicated by microbial biomass), habitat provision, and cultural benefits. It is the intent of this research to:

- i. Quantify the potential for carbon accumulation, biodiversity, microbial nutrient cycling, habitat provision, and cultural services in RSCs relative to that of reference ephemeral headwater streams,
- ii. Estimate the rates and extent of ecosystem service establishment over time using a chronosequence of RSC sites,

- iii. Compare ecosystem service potential in RSCs to that of other nature-based SCMs (i.e., stormwater wetlands) and conventional SCMs (i.e., wetponds), and
- iv. Provide engineering design characteristics to optimize specific ecosystems services from RSCs.

Ultimately, this research will help provide engineers, regulators, and planners with a holistic evaluation tool of RSCs as nature-based systems.

6.3 Methods

6.3.1 Site Selection

Nine RSCs in Maryland and North Carolina underwent ecosystem service indicator analysis during May of 2012 and 2014, resulting in a chronosequence of 14 RSCs between the ages of 1 and 14 years (Table 6-1). Due to the recent implementation and crediting of RSCs, a limited amount of sites are more than three years old. RSCs in Maryland (MD) were chosen based on recommendations from personnel from Biohabitats, Inc., who have been designing and installing RSCs in Anne Arundel County, MD, since 2000, including the first known RSC design (Howards Branch, 14 yrs). All the RSCs assessed in MD were designed by Biohabitats, Inc., and incorporated native plugs and plantings, local materials, and ecosystem restoration design. These RSCs were located in residential or highly urban watersheds. The RSCs located in North Carolina were built with the sole goal of mitigating storm flows and gave little consideration to peripheral ecosystem-enhancing design characteristics. Upon completion, the NC sites were mulched and seeded with a grass stabilization mix. One of the NC RSCs was located along a highway bridge over a stream and the other was located at a NC Department of Transportation rest area. The RSCs also varied in hydrology such that some were well drained, experiencing little to no extended surface ponding, while others were restored headwater streams experiencing year-round surface flow. For the purposes of evaluation, perennial flow systems were considered “wet” and well-drained or

seasonal ponding systems were considered “dry.” Two ephemeral headwater streams, one in NC and one in MD, were chosen as reference sites, as this environment was considered the most similar natural system to RSCs in terms of its function and appearance.

6.3.2 Ecosystem Service Indicators

6.3.2.1 Carbon Sequestration and Climate Regulation

Carbon sequestration plays an important role in stabilizing atmospheric greenhouse gas concentrations. Greenhouse gases are defined by their ability to emit or adsorb radiation within the thermal infrared range, and make life on earth possible by regulating temperature. Increases of anthropogenic greenhouse gas emission have been linked to the increased warming of the earth’s climate, causing concern for the functioning and survival of future generations. Furthermore, most projected scenarios of global energy usage show a continued increase in the emission of the greenhouse gas, CO₂ (IPCC 2005). Reducing the concentration of atmospheric carbon involves both the reduction of CO₂ emissions and the sequestering of CO₂ and other carbon sources such that they do not enter the atmosphere.

Aquatic ecosystems provide opportunities for carbon sequestration. Peatlands, which currently comprise 3 to 4% of the world’s land area are estimated to hold 1.5% of the total estimated global carbon storage, 25% of that stored in all terrestrial soil and vegetation (MEA, 2005b). More than a quarter of the carbon storage in these aquatic systems is contained in terrestrial vegetation and soils (MEA, 2005b). Brevik and Homburg (2004) have measured annual carbon accumulation rates in wetlands, including intertidal, salt marsh, freshwater marsh, Aeolian, and lagoon wetlands, as roughly 0.033 kg per square meter. Although streams have generally been viewed as a carbon source, as they carry eroded particulate organic matter, there has been very little research done on the role of small intermittent streams within the carbon cycle (Cole et al. 2007). Research in the Konza Prairie in Kansas measured soil organic carbon (SOC) levels in stream floodplains to be similar to that of grassland

Table 6-1 RSC and watershed characteristics for evaluated sits

RSC Name	Eval Year	Age	Location	Coordinates	Watershed Type	Watershed Area (ha)	% Imperv	RSC Length (m)	Hydrology
Alamance	2014	1	NC	36.063° N 79.534° W	Rest Area	1.6	63%	38	Seasonal Ponding
Central Sanitation	2012	1	MD	39.104° N 76.619° W	Commercial, High Residential	22	26%	152	Seasonal Ponding
Cabin Branch	2014	1	MD	38.993° N 76.550° W	Mediume Residential	4.4	55%	99	Seasonal Ponding
Brunswick	2014	2	NC	38.999° N 76.693° W	Agricultural, Low Residential	5.1	12%	40	Seasonal Ponding
Crofton	2014	3	MD	38.999° N 76.693° W	Commercial	72	33%	387	Annual Flow
Central Sanitation	2014	3	MD	39.104° N 76.619° W	Commercial, High Residential	22	26%	152	Seasonal Ponding
Carriage Hills	2012	3	MD	39.100° N 76.558° W	Medium Residential	5.7	21%	152	Well Drained
Carriage Hills	2012	5	MD	39.100° N 76.558° W	Medium Residential	5.7	21%	152	Well Drained
Homeport	2012	5	MD	38.966° N 76.545° W	High Residential	8.6	21%	23	Seasonal Ponding
Wilelinor	2012	6	MD	38.967° N 76.543° W	Commerical, Medium Residential	86	32%	250	Annual Flow
Homeport	2014	7	MD	38.966° N 76.545° W	High Residential	8.6	21%	23	Seasonal Ponding
Wilelinor	2014	8	MD	38.967° N 76.543° W	Commercial, Medium Residential	86	32%	250	Annual Flow
Howards Branch	2012	12	MD	39.020° N 76.549° W	Low Residential	92	7%	180	Annual Flow
Howards Branch	2014	14	MD	39.020° N 76.549° W	Low Residential	92	7%	180	Annual Flow
Annapolis	2014	Ref	MD	39.022° N 76.553° W	Wooded	0.6	0%	38	Well Drained
Umstead Park	2012	Ref	NC	35.871° N 78.762° W	Wooded	1.1	8%	79	Well Drained

prairies (Ransom et al. 1998), which have measured carbon sequestering rates up to 0.6 Mg C ha⁻¹ yr⁻¹ (Schuman et al. 2002).

As portions of the RSC are intermittently flooded, this SCM may act similarly to wetlands or floodplains in its ability to sequester. Several studies suggest that carbon sequestration may occur in restored aquatic systems, especially in wetland-like environments (Craft *et al.*, 1999; Craft *et al.*, 2003; Underwood *et al.*, 2005). Carbon sequestration by RSCs were evaluated based on carbon measurements taken over time at the chronosequence of sites, as set forth by Euliss *et al.* (2006) and used in SCM ecosystem service evaluation by Moore and Hunt (2012). At each site, a series of three transects were established from the inlet to the outlet, thus spanning the length of the RSC (Figure 6-3). Transects incorporated the “flood plain”, pool, and riffle portions of the RSC. Along each transect, a total of three soil cores were collected from the upper 10 cm of the soil profile using 48 mm diameter steel soil cores. Soil cores were oven-dried at 105° C for 48 hours and weighed to determine bulk density. Samples were then ground, passed through a 2-mm sieve, and sent to NCSU Environmental and Agricultural Testing Service (EATS) Laboratory for quantification of % carbon. Carbon is reported in terms of soil density (g C per kg soil) and areal density (g C per m²).

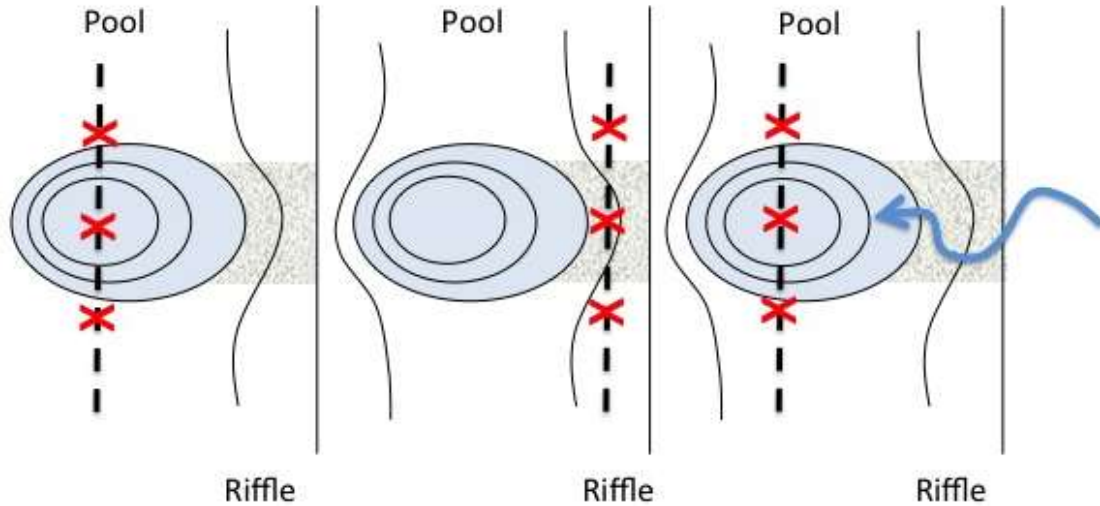


Figure 6-3 Planview transects along RSC used for carbon and microbial biomass samples, as well as vegetation enumeration.

6.3.2.2 Nutrient Cycling and Soil Formation

Nutrient removal mechanisms in natural aquatic systems include sedimentation of particle bound nutrients, microbial metabolic processes, and plant uptake.

Mulholland (1992), in examining a segment of a forest stream in Tennessee, found that microbial metabolism is the predominant mechanism for nutrient removal in the upper soil layers. Nutrient removal in an aquatic ecosystem requires slow water velocities and vegetative filtration to 1) capture and detain the particle-associated nutrients and 2) allow for microbial communities to contact the water. Microbes must be present in the soil to metabolize organic N into plant available nitrogen for immobilization. The size of microbial biomass within the soil profile is a sensitive indicator of soil health, and may be more accurate in natural conditions where nutrients are immobilized in living biomass than in a soil fertility test where only soil nutrients are measured (Paul, 1984; Jordan, 1985). Microbial biomass measurements have been used to monitor both soil quality decline due to land

alterations (Sparling et al., 1994a, Sparling et al., 1994b) and soil recovery due to ecosystem restoration (Ross et al., 1992; Insam and Domsch, 1988). Nutrient removal in natural stream systems primarily occurs in shallow pools, at stream banks, or around structures/debris during low flow (Groffman et al. 2005; Bukaveckas 2007) and interactions with a floodplain during higher flow (Kaushal et al. 2008), all elements which may be present in RSCs.

The majority of microbial biomass in a soil profile is located in the top 10 cm (Murphy et al., 1998). Microbial biomass in RSCs were measured taking samples using soil cores to a depth of 10 cm at each carbon sampling location along the transect, collectively including a pool, floodplain, and riffle portion of each RSC. Samples underwent the fumigation-extraction procedure, as described by Rice et al. (1996). Microbial biomass is presented in terms of total microbial carbon and nitrogen per soil mass, as well as the microbial quotient (microbial C/N per total C/N). As this indicator has not been measured in SCMs previously, results from RSCs are compared to sampled reference sites and other comparable sites in the literature (Sparling, 1997).

6.3.2.3 Biodiversity

Biodiversity supports the wellbeing of humans by maintaining stable and balanced ecosystems which are able to provide humans with additional services (Daily et al. 1997). Required for functioning ecosystems, biodiversity often functions as an indicator of ecosystem health (Zedler, 2000), and has been linked to other important ecosystem services such as pest control (Hunt *et al.*, 2005) and education and recreation potential (MEA, 2005b). In a healthy aquatic ecosystem, a variety of mayflies and caddisflies, which are more sensitive to pollutants, would be present; whereas, an impaired aquatic ecosystem is dominated by midges, limpets, and snails, which have a high degree of resistance to pollutants (DeShon 1995). RSCs are not consistently wet or dry, such that benthic macroinvertebrates could not be used to determine biodiversity. This research focuses on vegetative biodiversity. As

described by Moore and Hunt (2012), vegetation biodiversity was determined by randomly placing a 0.5-m² square quadrat in the vicinity of the carbon assessment transects. All vegetation growing within the quadrat was identified and enumerated at each of three sampling points. Species that were not identified in the field were collected and pressed for subsequent keying. Species richness and evenness were calculated using the Shannon-Weiner diversity index (Dodds, 2002).

6.3.2.4 Habitat Provision

Habitat provision is related to biodiversity in that it supports a variety of species which are able to supply services to human populations. However, habitat provision is important in itself because it affects species of different trophic levels differently. Holt et al. (1999) found that due to higher area requirements, species of higher trophic levels decline faster as their habitats deteriorate than those of lower trophic levels. Dobson et al. (2006) describes a model that predicts species decline relative to habitat remaining. Results showed that although an order of magnitude loss of habitat only results in a 50% loss in species number, the majority of this loss in the highest trophic level, resulting in an average decline of one trophic level. Therefore, examining habitat persistence may give a clearer picture of the health of the ecosystem.

Many urban areas have destroyed natural habitats, which are important for different species survival. Underwood et al. (2005) documented the provision of the almost extinct Atlantic White Cedar in the Chesapeake Bay watershed by using an RSC to manage the incoming stormwater runoff from surrounding urban areas. To determine RSC ability for habitat provision, habitat services provided by each of the sites will be assessed using a rapid assessment rubric of indicators of habitat quality adapted from NC DEHNR (1995), shown in Figure 6-4. Visible indicators across the entire RSC footprint were used to assign a score from 0 to 5 to each site. Habitat indicators include vegetation structure, food value of vegetation for wildlife, natural

space and connectedness, and other direct observations of wildlife (i.e. nests, tracks, scat, etc.).

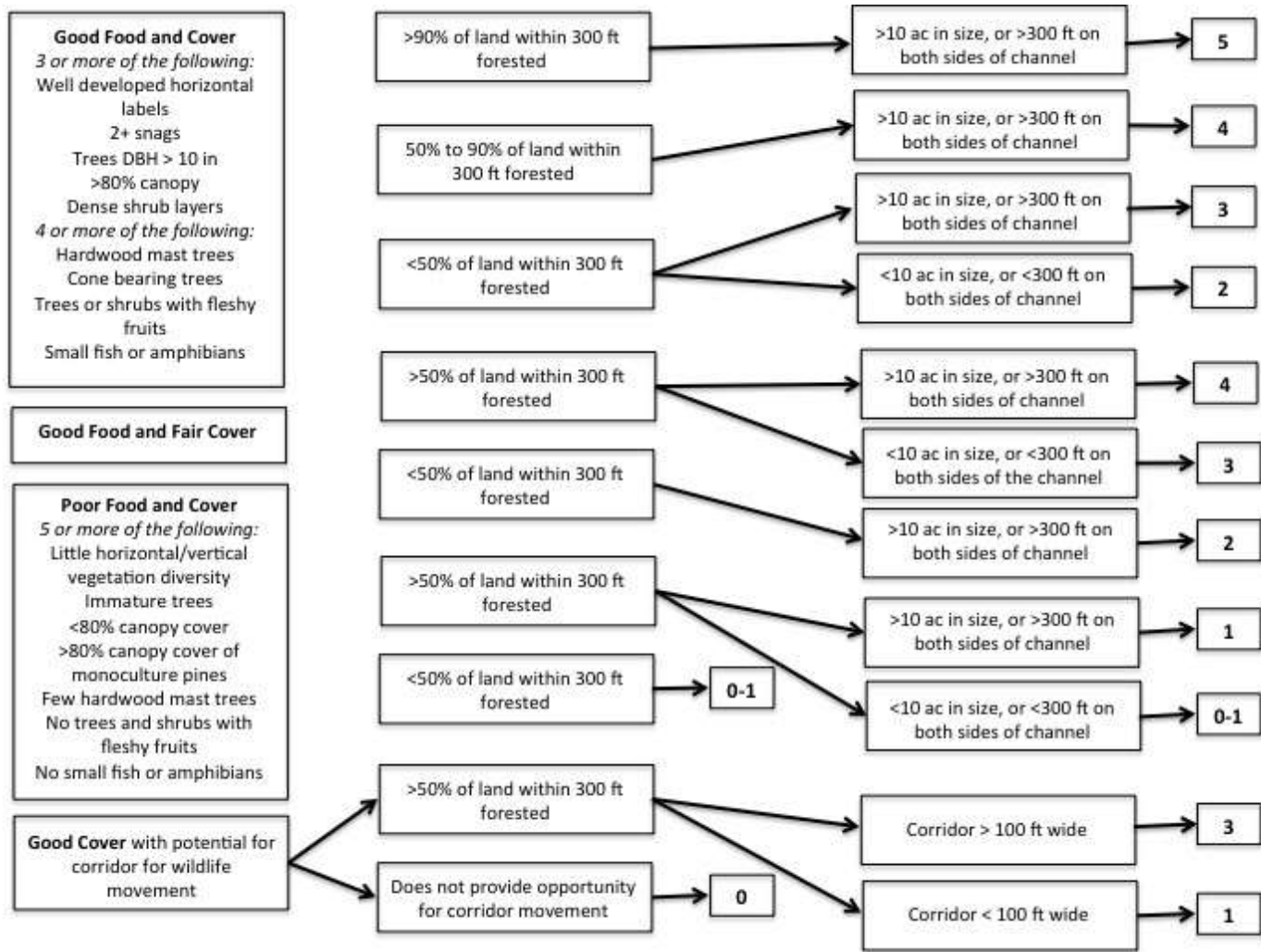


Figure 6-4 Habitat rating map based on wetland habitat guidance from NC DEHNR (1995).

6.3.2.5 Cultural Services

Cultural services including recreation and education were valued second only to flood control by the general public's review of benefits provided by constructed wetlands (Ghermandi et al., 2010). It is possible that these values may extend to other similar vegetated engineered ecosystems, like RSCs. Cultural services were evaluated using the rapid assessment rubric described by Moore and Hunt (2012) (Table 6-2). Elements of design important to recreation include public accessibility, physical accessibility, and recreational infrastructure. Elements of design important to educational benefits include proximity to schools or educational centers, history of use for educational purposes, and the presence of educational infrastructure. Each element was assessed across the entire RSC footprint, and rated on a scale of 0 to 4. The final score was calculated by taking the average score of each element.

6.3.3 Statistics

Raw data and log-transformed data for each service were tested for normality using the Shapiro-Wilks Normality Test. Normal distributions were confirmed for all data except microbial biomass. Sites were categorized into age bins described in Table 6-3. The t-test for normally distributed data and the Wilcox test for non-normal data were used to identify significant differences between ecosystem service results in each age bin. Linear regression analysis was used to estimate establishment rates and extent of each service over time. Additionally, RSCs were divided into "wet" and "dry" systems, as described previously, and significant differences in ecosystem services values were compared between the two types of RSCs using the t-test or the Wilcox test. Ecosystem service values relative to watershed imperviousness were also tested using t- and Wilcox tests, as well as linear regression. Acceptable Type I error was considered less than 5% ($\alpha < 0.05$). Although, given the limited amount of RSC sites available for examination, differences with type I error up to 10% are mentioned ($\alpha < 0.1$).

Table 6-2 Scoring criteria for cultural service assessment used in this and previous SCM ecosystem assessment, as presented in Moore and Hunt (2012)

Score	4	2	0
Recreation Subcategories			
Legal Accessibility	Open access to public	Public access by permission only	Prohibited public access
Physical Accessibility	Access is not restricted by physical barriers Site is highly visible	Physically accessible, but not highly visible	Access is physically restricted by fence, steep embankment, etc.
Recreational Infrastructure	Recreational infrastructure (i.e. trails, viewing areas) is present and well maintained	Recreational infrastructure present, but not well maintained	Recreational infrastructure not present or so poorly maintained as to present safety hazard
Education Subcategories			
Location	Located on campus of school or educational center	Located <2km from school or other education center	Located >2km from school or educational center
History of educational use	Site actively used (1 or more time per yr) for educational or research purposes	Infrequent educational use	No history of educational use
Educational Infrastructure	Educational infrastructure (i.e. signs, activity stations) present and well maintained	Educational infrastructure present, but poorly maintained (i.e. cannot read sign due to fading or blockage)	Educational infrastructure not present

Table 6-3 Age bin distributions with estimated service establishment

Age	Possible Established Services	Source
0 to 4 yrs	Water quality mitigation Hydrology mitigation Cultural Services	Craft et al., 2003 Browning et al., 2008 Chapter 3, Chapter 4
5 to 9 yrs	Biodiversity Habitat provision	Craft et al., 1999 Craft et al., 2003
10 + yrs	Soil structure Soil carbon and nitrogen pools Soil microbial biomass	Craft et al., 1988 Craft et al., 1999 Craft et al., 2003
Reference	Fully established	

6.4 Results

6.4.1 Carbon Sequestration

Carbon content in RSC soils varied between 0, where little or no soil accumulation occurred, to 133 g C per kg of soil. Soil in the center of the pool was composed of the greatest percent carbon (2.78%), significantly greater than that found in the center of the riffle (1.40%) or the floodplain (1.50%). In wet RSCs, where surface flow is perennial, the center of the riffle was exposed cobble such that no soil was available for sampling, and carbon content was considered zero. The sides of both the riffles and pools saw similar soil carbon, both in terms of percent carbon, carbon density, and areal carbon.

Soil carbon density (g C per kg soil) increases with system age (Figure 6-5). Significant differences were measured in the top 10 cm of soil for RSCs less than 5 years old and those greater than 10 years old. When the allowance of Type I error is expanded to 10%, significant differences in carbon density in the top 5 cm of soil exist for all age bins. Carbon accumulation in soil occurs from the top down via deposited and broken down organic matter, therefore differences in the 5 cm of soil should be more emphasized than in lower soil profiles over such a short time frame. Carbon densities for RSCs in all age bins were significantly different than reference sites, consistent with previous findings that carbon pools and soil structure in restored ecosystems establishes much later in the ecosystems life, or perhaps never at all (Craft et al., 1999; Craft et al., 2003). Regression analysis found a best-fit line with an annual soil carbon density increase of 2.13 g C per kg soil (Figure 6-6a). When soil carbon is converted to areal density, there is no clear correlation with RSC age. This is a result of the differences in soil bulk density between well-drained terrestrial soils and saturated or submerged soils. In RSCs, soil cores taken from the center of a wet pool had 3 to 5 times lower bulk densities than those taken along the sides of a pool or a riffle. Since areal carbon is the percent carbon in the soil multiplied by the bulk density, terrestrial soils will have higher areal carbon content

than saturated soils, often even if the percent carbon of the saturated soil is higher. Moore and Hunt (2012) found similar results in areal densities of submerged areas of wetland and wetponds, as compared to terrestrial areas of the same SCMs. When examining areal carbon of dry RSCs (only seasonal submerging of soils), a stronger correlation exists ($r^2 = 0.45$ vs. $r^2 = 0.03$) (Figure 6-6b). Data is only available for dry RSCs up to 7 years old, so the slope of this correlation is likely not accurate across the entire RSC lifespan.

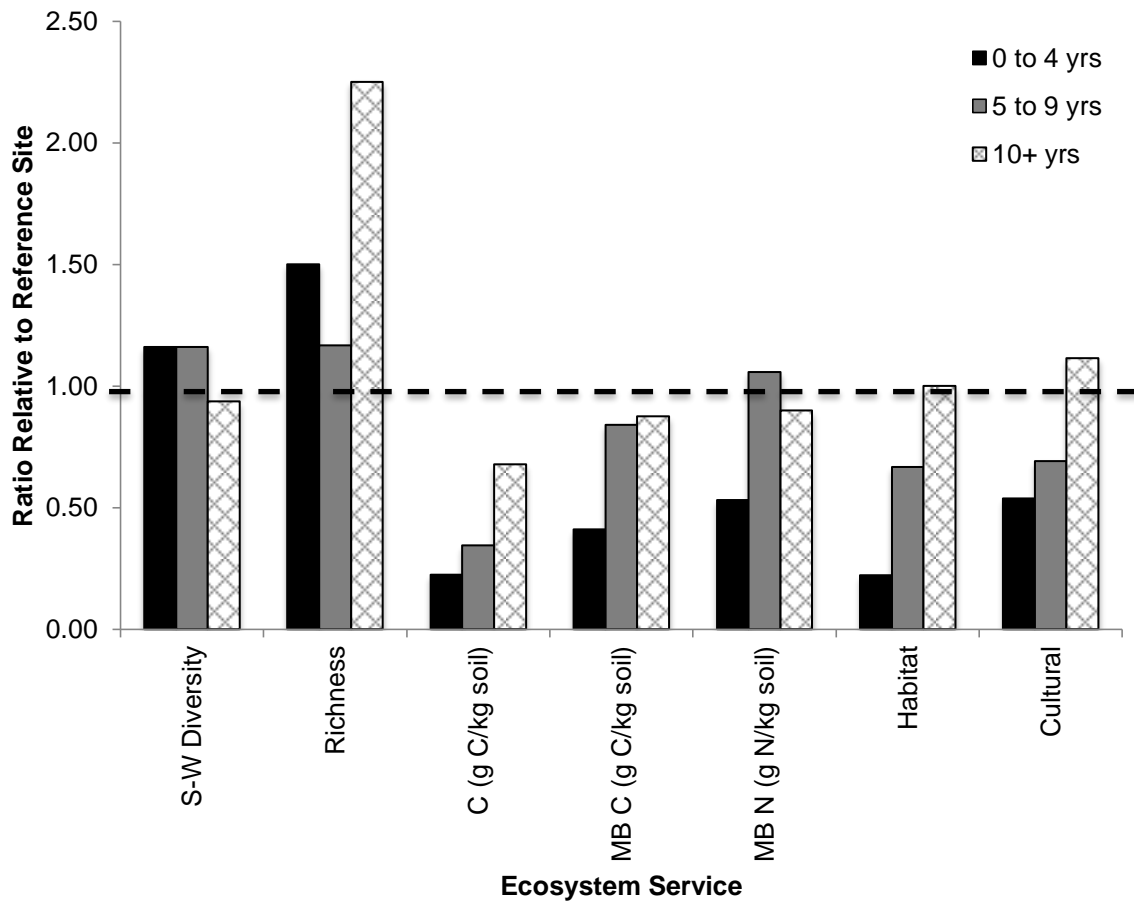
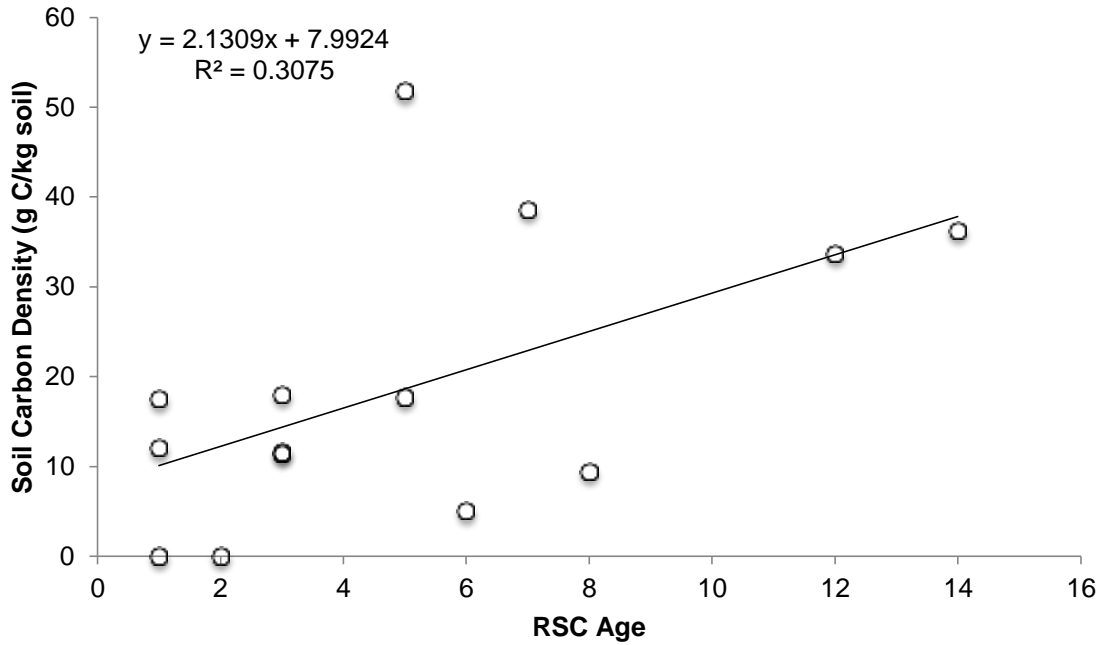
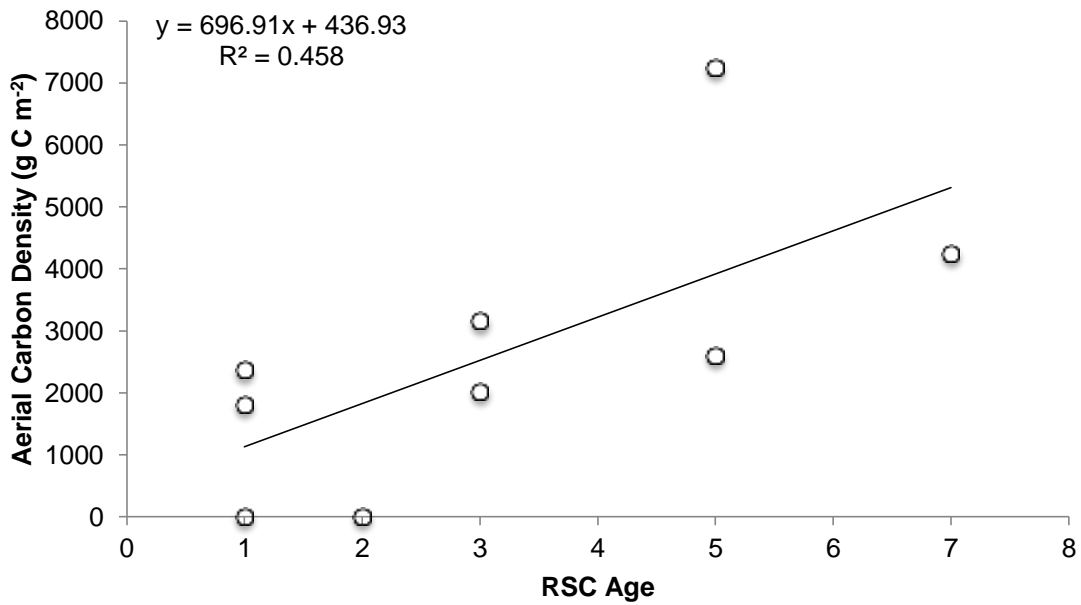


Figure 6-5 Ecosystem service values for each age bin relative to reference site



(a)



(b)

Figure 6-6 Best-fit linear correlation between RSC age and soil carbon density in all RSCs (a) and areal carbon density in dry RSCs (b).

Soil carbon content in RSCs exceeds that found in both CSWs and SWPs, as evaluated by Moore and Hunt (2012) (Table 6-4). The mean fraction of soil carbon in RSCs is the same as that found in CSW, but as mentioned previously, RSCs are more terrestrial than CSW, and therefore have an overall higher areal carbon density. The accumulation of carbon in RSC over the first 7 years is significantly higher than that measured in any portion of a CSW or SWP by nearly a magnitude. This may be a result of implementation practices. CSWs in North Carolina are often amended with organic soil during installation (NC DENR, 2009). Therefore, differences in carbon content between the first year and later years may not be so dramatic. RSCs, on the other hand, are not initially amended, but rather soil portions of the systems are covered with a layer of hardwood mulch. Furthermore, RSC installation is generally along a linear path and relatively non-invasive compared to CSW installation, such that even a young RSC may have sufficient canopy cover to add further carbon sources to the system (i.e. leaf fall). Therefore, a new RSC will likely have very little in terms of carbon accumulated on its soil surface. However, as evidenced herein, given several years, the mulch and additional leaf litter will break down resulting in a thick organic soil horizon.

The same accumulation rates are not observed in roadside vegetated filter strips/vegetated swales (VFS/VSs) or wetland swales (WSs). As with RSCs there is often no organic carbon added to these systems. The carbon areal densities in RSCs are similar to that measured in roadside VFS/VS between 1 and 33 years old in the NC Piedmont (Bouchard et al., 2013). However, much higher densities were measured in VFS/VSs and WSs in the NC Coastal Plain. Despite the fact that the mean age of VFS/VS and WS studies was 17 years, significantly greater than that of either RSCs or CSWs studied, another possible reason for the difference in mean densities may be related to the elevated atmospheric CO₂ along roadsides, especially interstate highways. Higher soil carbon densities have been observed in shallow soils of carbon-enriched forest and grassland plots, as compared to control

plots (Hungate et al., 1997; Sclesinger and Lichter, 2001). Carbon enriched soils were also dominated by anthropogenic carbon isotopes (C^{13}). The mean carbon accumulation rate for all VFS/VS was $99 \text{ g C m}^{-2} \text{ yr}^{-1}$, higher than that of CSWs or SWPs. The dry RSC areal carbon regression line (Figure 6-6b) continues to provide a much higher carbon accumulation rate, such that it is possible for dry RSCs to reach similar (or perhaps greater) areal carbon densities to those of coastal VFS/VSs and WSs within 7 years of construction. The RSC site representing the density increase between 5 and 7 years in Figure 6-6b happens to be the smallest RSC, located alongside a two-lane county highway (Homestead); the higher areal carbon rates observed in dry RSCs, in part, may also be due to elevated atmospheric CO_2 . If this datum is eliminated, accumulation is estimated closer to $400 \text{ g C m}^{-2} \text{ yr}^{-1}$ for the first 5 years of an RSCs lifespan, still 4 times higher than that observed in VFS/VS.

Table 6-4 Carbon content comparisons in RSCs to other SCMs

	% C, soil	Areal Density in top 10 cm of soil (g C m^{-2})	Regression coefficients, C accumulation ($\text{g C m}^{-2} \text{ yr}^{-1}$)
RSC	2.02	2263	697^1
Wetland	2.04^2	1671^2	83^2
Wetpond	0.58^3	536^3	14^3
VFS/VS (NC Piedmont) ⁴		2550	99
VFS/VS (NC Coast) ⁴		4140	99
WS (NC Coast) ⁴		5040	99

¹ Accumulation for dry RSCs only

² From Moore and Hunt (2012), weighted average of wetland zones based on 20% open water, 40% shallow water, and 40% shallow land or land (NC DENR, 2009)

³ From Moore and Hunt (2012), weighted average of wet pond zones based on 80% open water, 10% shallow water, 10% shallow land

⁴ From Bouchard et al. (2013)

The rapid accumulation of soil carbon in RSCs is encouraging. However, the likely carbon sources of this initially accumulated carbon are likely of the labile, or easily

decomposed, fraction. The fact that it is easily decomposable means that it will likely not contribute to long-term soil carbon pools, and therefore, long-term carbon sequestration. One recalcitrant, or less easily decomposable, carbon precursor is alkyl C, found in the bark of woody plants and plant roots (Lorenz et al., 2007). Incorporating woody biomass and plants with high root-to-shoot ratios into the design can easily increase RSC recalcitrant carbon accumulation. Incorporating woody biomass and high root-to-shoot ratio vegetation is not an option in other SCMs (e.g., SWP, VFS/VS, WS). While many of the MD RSCs assessed did incorporate these plant types, the effects on carbon pools will likely need more time than the age of most of the RSCs examined, which is reflected by stagnant soil carbon in the lower 10 cm of the soil profile. Ultimately, the initial soil carbon accumulation rate in an RSC is higher than what is actually experienced in either reference sites or other SCMs with and without initial soil carbon amendments. It is important to note, however, that although the accumulation rate in RSCs may not be sustained over its entire life (as observed by Bouchard et al., 2013), evidence is strong that RSC do accumulate large quantities of soil carbon during early establishment, a factor necessary for long-term (recalcitrant) carbon storage over time.

6.4.2 Microbial Biomass

Microbial biomass carbon (MBC) accounted for 8 to 779 ug per g of soil, with a median quantity of 140 ug/g (Table 6-5). Microbial biomass nitrogen (MBN) accounted for 2 to 160 ug/g, with a median quantity of 28 ug/g. The microbial carbon found in RSCs is similar to that measured in woodlands of sandy loam soils in Washington (Sparling et al., 1994a). MBC/MBN ratios varied from 1.7 to 11.8, similar to those observed in other studies (Maithani et al., 1996; Moore et al., 2000; Haripal and Sahoo, 2014). MBC/organic carbon ratios varied between 0% and 21%, with a median value of 1%, lower than values observed in other studies on similar soils (Sparling et al., 1994). Lower MBC/organic carbon ratios may suggest the organic carbon pool is composed of higher labile, or highly decomposable, carbon than

natural or more established ecosystems (Haripal and Sahoo, 2014), which correlates well with the high soil C accumulation rates observed at in RSCs.

Table 6-5 Microbial biomass measurements and biodiversity indices across RSC age bins

Age	MBC (ug kg ⁻¹)	MBN (ug kg ⁻¹)	MBC Quotient	MBC:MBN
0 to 4 yrs	97	23	1.06%	5.04
5 to 9 yrs	198	46	0.97%	4.50
10+ yrs	207	39	1.21%	5.83
Reference	236	43	1.18%	5.65

MBC in soils from RSCs younger than 5 years old was significantly different than measured in older RSCs or the reference sites. Median MBC in the newly constructed RSCs was 97 ug g⁻¹, where the median for RSCs older than 5 years was 198 ug g⁻¹, representing a 100% increase in MBC within the first five years. Haripal and Sahoo (2014) saw similar increases between former Indian agricultural lands 2 years and 6 years into succession. Unlike the RSCs studied herein, Haripal and Sahoo (2014), continued to see increases in MBC as sites progressed through succession, measuring median MBCs densities greater than 500 ug g⁻¹ at year 15. It should be noted that MBC densities observed in temperate forests in North Carolina range from 50 ug g⁻¹ in mineral soils to 450 ug g⁻¹ in litter (Gallardo and Schlesinger, 1994), much less than that observed in native tropical forests (Sparling et al., 1992; Yang et al., 2010). Additionally, the reference sites in this research measured similar MBC and MBN densities, MBC/MBN ratios, and MBC quotients as those measured in RSCs more than 5 years old (Figure 6-5). It is possible, therefore, that soil microbial communities did not continue to increase in RSCs beyond 5 years because they had already reached the sustained density. As microbial biomass is considered an early indicator of changing soil processes, the fact that the microbial communities in RSCs after 5 years are similar to reference sites suggest that

nutrient cycling and soil organic carbon in RSC may reach similar densities as those measured in reference sites.

6.4.3 Biodiversity

Shannon-Wiener indices varied between 0.95 and 2.2, with no correlation to system age (Figure 6-5). Species richness varied between 3 and 19, also with no correlation to system age. Results may reflect the limitations of using a single quadrat size despite the widely varying vegetation types. Several of the oldest RSC (Howard's Branch, Wilelinor) were dominated by the endangered Atlantic White Cedar, of which, due to their size, only saplings could be represented in the quadrat counts. Very little undergrowth was present below adult Atlantic White Cedars, resulting in low diversity measurements for that particular quadrat. On the other hand, planted young sites in early succession (Central Sanitation, Crofton) contained intended vegetation (ferns, sedges, rushes), as well as early succession herbaceous plants (clovers and partridge pea, *Camaecrista fasciculata*) and weeds (such as Japanese Stilt grass, *Microstegium vimineum*), which increased the quadrat biodiversity indices. Reference sites tended to be more tree dominated as well, which, similar to more established RSCs, resulted in low quadrat biodiversity, likely not reflective of the ecosystem as a whole. Despite limitations, species richness and Shannon-Wiener indices in RSCs are similar to median values observed in CSWs, and exceed those measured in SWPs (Moore and Hunt, 2012). As vegetative biodiversity is strongly connected to nutrient cycling and microbial biomass (Craine and Wedin; 2002; Zak et al., 2003; Carlisle and Clement, 2005), the SCMs with more biodiversity, like RSCs or CSWs, will likely establish additional ecosystem services quicker and more extensively.

6.4.4 Habitat Provision

Habitat quality in RSCs ranged from 0.5 to 5. Differences were observed between all RSC age groups with p-values of 0.051 to 0.11 (Figure 6-5). Sample size was limited to one data point for each RSC analysis, and, given more available data points, p-

values may decrease to below 0.05. As habitat ratings were driven, in part, by available food (i.e., fruit producing vegetation) and cover (i.e., canopy, fallen logs), RSCs inevitably require a period of establishment before these aspects are available. Animal sightings, including water snakes, frogs and tadpoles, ducks, and deer, were documented during the May 2014 visit to the oldest, most established RSC (Howards Branch, 14 years). This site received a rating of 5, indicating that it is possible for RSCs to provide habitat similar to that observed in natural ecosystems. It is important to note, however, that the ability of an RSC to provide habitat is limited by the size and immediate surroundings of the RSC, such that small, highly urban RSCs (i.e., Brunswick, Alamance) will probably be unable to establish a habitat rating exceeding 2 or 3.

6.4.5 Cultural Benefits

Cultural ratings in RSCs varied between 0.6 and 2.3, with significant differences observed between RSCs younger than 10 years and those older than 10 years, when type I error is set at 10% (Figure 6-5). In the case of RSCs, most cultural strengths were observed when they were close to people, and in some cases schools. They were often located in public spaces and incorporated into walking areas, increasing the recreational potential of RSCs. Median RSC recreation scores were 2.3 for RSCs less than 10 y, and 3.2 for RSCs greater than 10 years. When recreational infrastructure, such as bridges and walking paths, were present, they primarily included thick wood boards and worn footpaths, clearly created by neighborhood residents frequenting the RSC, contrasted with more permanent infrastructure incorporated into initial design plans. Median RSC education scores were 0 for RSCs less than 5 years, 0.7 for RSCs between 5 and 10 years, and 1.7 for RSCs greater than 10 yrs. RSCs showed little to no educational use or infrastructure. When active RSC engagement with education did exist, it was due to university research. RSC cultural ratings were similar to those observed in SWPs, and less than those for CSWs (Moore and Hunt, 2012). As cultural criteria are somewhat dependent on infrastructure incorporated with the design of the SCM

(e.g., walking paths, benches, signage), the data suggest that RSCs, like SWPs, are often solely viewed as an SCM, and not considered for other potential cultural benefits. On the other hand, CSWs seem to either provide more opportunity or be inherently chosen for the additional cultural benefits available. As RSCs are measure similar to CSWs in all previous services analyzed, it is possible that RSCs are being under-utilized as cultural assets.

6.4.6 Wet and Dry RSCs

Despite similar design components, RSCs with annual surface flow (“wet”) were, in many ecosystem aspects, quite different from RSCs that had seasonal ponding or were well drained (“dry”). For the sites evaluated, 14% of RSCs less than 5 y old, 40% of RSCs between 5 and 9 y, and 100% of RSCs 10 y or greater were considered “wet”, creating an unequal distribution of “wet” RSCs across the chronosequence. Ecosystem services were compared between the two different types (not parsed into age bins) of RSCs to determine hydrology as a possible confounding factor to ecosystem establishment results described herein. Wet RSCs had significantly higher MBC density, as well as habitat and cultural ratings (Figure 6-7). Microbial community density may decrease when soils remain dry for extended periods of time (Smith et al., 1990; Haripal and Sahoo, 2014). However, both wet and dry MBC were similar to values observed in literature (Gallardo and Schlesinger, 1994; Sparling et al., 1994). Habitat ratings in “wet” RSCs were also consistently higher than those observed in “dry” RSCs. Aspects contributing to habitat that differed between the two hydrologies included the availability of tree fruits (likely related to system age) and the size of the RSC. The “wet” RSCs were also the longest RSCs assessed (Table 6-1), which does not always affect hydrologic design, except in the case of Howard’s Grove. This RSC had a very shallow slope over a long RSC length, necessarily resulting in large pools where water was stored and short riffles to accommodate the design, and likely contributing to its overall “wetness”. An increased water level in RSCs also offers a variety of hydrologic zones, including terrestrial, shallow water, and deeper water (similar to those in

wetlands), which would offer more opportunity for both aquatic and terrestrial flora and fauna, increasing the habitat variety (and thus potential) of the RSC. Cultural differences between “wet” and “dry” RSCs were primarily observed in terms of recreational infrastructure. Studies show that people have positive associations with water bodies, such as lakes or streams (Kaltenborn and Bjerke, 2002), which may be why community-created recreational infrastructure existed at the “wet” RSCs.

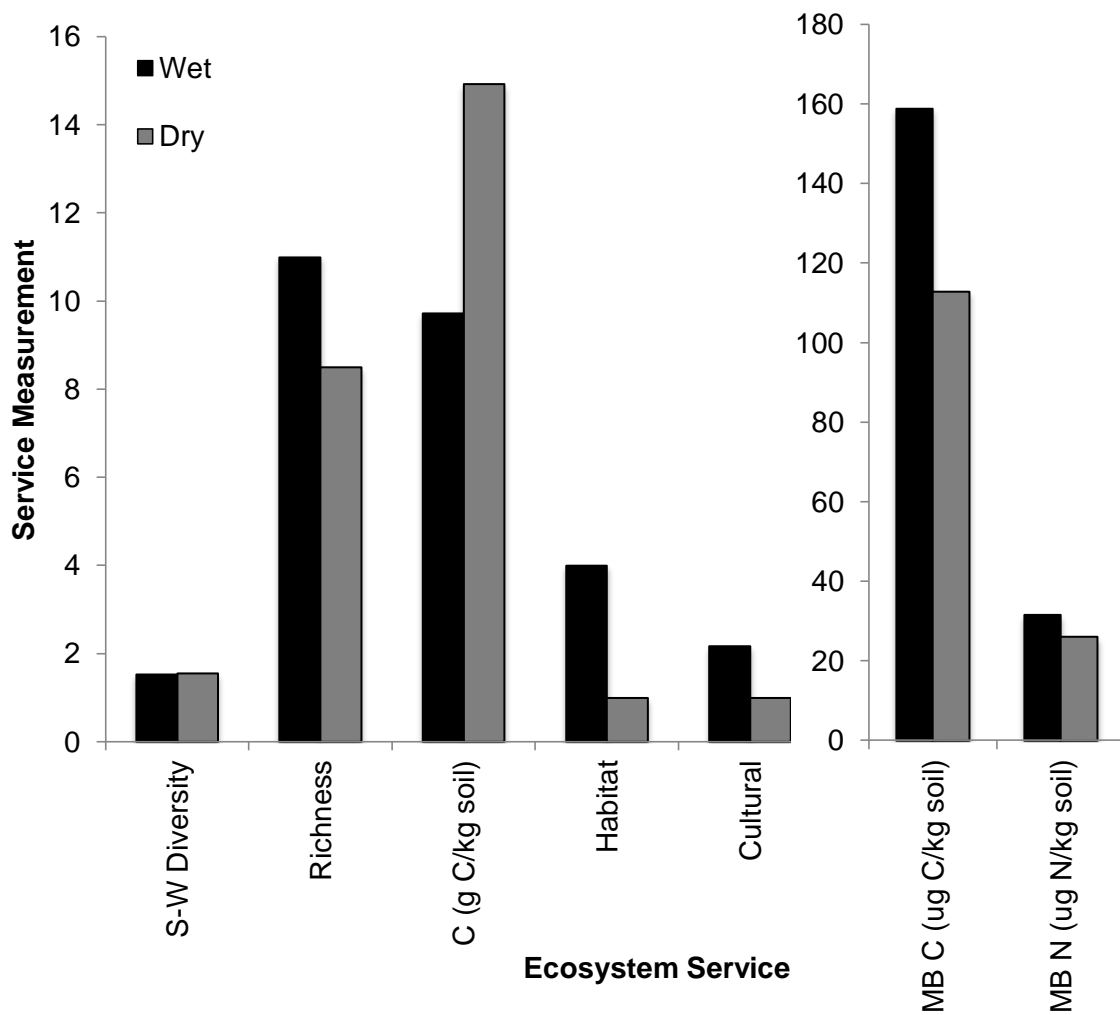


Figure 6-7 Median values for ecosystem services in wet and dry RSCs

6.4.7 Imperviousness and Ecosystem Services

Watershed characteristics may also have an influence on ecosystem service provision in RSCs. Increased watershed imperviousness results in flashier, more polluted runoff contributions to RSCs (Arnold and Gibbons 1996; Walsh et al. 2005; NRC 2009). Watershed imperviousness was also not equally distributed across the chronosequence, with mean imperviousness of 26%, 21%, and 7% for RSCs less than 5 y, between 5 and 9 y, and 10 y or more, respectively. Habitat ratings are significantly higher when watersheds are less than 15% impervious (Table 6-6). This may be related to the fact that important aspects of highly rated habitats are the size and connectedness of the natural space (NC DEHNR, 1995). Watersheds with higher imperviousness have less natural space available, and roadways or parking areas can often disconnect available natural spaces. Interestingly, carbon accumulation significantly decreased as watershed imperviousness increased from less than 15% to between 15% and 30%, to greater than 30%. There may be several reasons for this correlation. First, less organic material will enter an RSC in an highly impervious watershed, as the watershed is less of a source of detritus and soil. Second, because flows from impervious surfaces are flashier, with higher peak flows, accumulated carbon may be more frequently flushed from the RSC. Third, RSCs in more pervious watersheds were also the older/ more established RSCs. It is difficult to tease out which of these factors may contribute most to carbon accumulation in RSCs; this thus requires further research with potentially confounding imperviousness more equally distributed between age bins. Carbon accumulation in other SCM environments with some similar characteristics to RSC has been documented (Moore and Hunt, 2012). Therefore, some amount of soil carbon content in RSCs should be attributed to their age, but watershed imperviousness likely has some effect on accumulation rates over time.

Table 6-6 Median ecosystem values for RSCs with different watershed imperviousness

Watershed Imp	SWIndex	Richness	Soil C (g kg ⁻¹)	MBC (ug g ⁻¹)	MBN (ug g ⁻¹)	Habitat	Cultural
0 to 15%	1.29	9.75	43.30	722	139	3.60	1.83
15% to 30%	1.73	9.00	24.93	652	158	1.58	1.03
30%+	1.47	10.00	8.53	583	130	2.30	1.80

6.5 Discussion & Design Considerations

Despite being designed for stormwater mitigation, this research has shown that RSCs indicate the provision of suite of additional ecosystem services. Research on young RSCs show that, with the exception of some initial nutrient flushing, RSCs are able to mitigate storm flows both in terms of hydrology and water quality within the first year (Chapter 3, Chapter 4, Chapter 5). Within the first five years, RSCs show similar MBC and MBN densities as those observed in nearby reference sites, and within the range of densities observed in similar ecosystems (Gallardo and Schlesinger, 1994). This suggests that, although carbon pools in young RSC soils do not match those of more established RSCs or reference sites, the processes are in place to cycle nutrients and build up carbon pools. From an areal density perspective, RSCs can have similar carbon content as reference sites after 5 years of establishment. This may be due to the high biomass turnover in early succession, as is relative to biomass contributions in fully established ecosystems (Bazzaz, 1979), but is likely composed of primarily of labile carbon until vegetation in RSCs is more fully established. Soil carbon distribution through the soil profile (as represented by soil density) increases as RSCs age, but not to the extent measured in reference sites by age 14 (Figure 6-5). This is not surprising, as previous research on restored ecosystems has shown carbon pool establishment to take 30 years or more to occur (Craft et al., 2003). Habitat provision ratings also increased as RSCs

aged, with the potential of achieving equal ratings to those of reference sites by age 14. Many highly urban RSCs, such as those with watershed imperviousness greater than 15%, will never establish beyond that of habitat for small, urban wildlife (i.e. squirrels, rabbits, birds), as natural space and connectivity are required habitat characteristics for larger fauna at higher trophic levels (Holt et al., 1999). Even then, pollution from highly urban areas may be harmful to fauna (Bishop et al., 2000), additionally inhibiting ecosystem function or benefit provided by the fauna.

This research shows that biodiversity and cultural benefits depend on how each is integrated into the initial RSC design. RSCs, like wetlands, incorporate many characteristics that may motivate public visits (i.e., water, diverse vegetation), but specific design elements (e.g., walking paths, bridges, educational signage) must be included to make RSCs more inviting, engaging, and accessible for optimization of recreation and cultural services. Exfiltration trenches (Chapter 4) or deep baffle weirs, can force the RSC to pond for extended periods, hence creating wetland-like conditions. When RSCs are “wet” or have seasonally ponded waters, the combination of wet and dry environments offer potential for *both* aquatic and terrestrial fauna and flora. Seasonal ponding will also increase MBC, % soil carbon, and water treatment benefits (herein, Chapter 4). The presence of surface water may also increase recreational or educational interest in RSCs, but the sites should include adequate infrastructure (e.g., signage, pathways) for both access and guidance to “cue” people through the RSC (Nassuer, 2004). Additionally, similar to wetlands, biodiversity may be greater when RSC are intentionally planted with a variety of native plants (Moore and Hunt, 2012), as opposed to natural establishment or seeding.

It is difficult to realize the extent to which additional ecosystem services may add value to an SCM. Costanza et al. (1997) used valuations done by previous studies on different ecosystems to estimate unit value of select services for a variety of

specific ecosystems. Global ecosystem value was estimated to be \$33 trillion (in 1994 US dollars). As RSCs tend to have some seasonally wet portions, but are often vegetated by trees, they may provide ecosystem value similar to that of floodplain wetlands and/or terrestrial forests. A summary of Costanza et al. (1994)'s findings for these ecosystems is presented in Table 6-7. If the actual value of RSCs for each age category can be calculated by multiplying the value of the cognate natural ecosystem (provided by Costanza et al., 1994) by the median fraction that the RSCs provide the service relative to nearby reference sites (Eq. 6-1),

$$V_{ES,RSC} = (V_{ES,NS}) (R_{RSC/NS}) \quad \text{Eq. 6-1}$$

where, $V_{ES,RSC}$ is the value of the ecosystem service in RSCs
 $V_{ES,NS}$ is the value of the ecosystem service in natural ecosystems per Costanza et al. (1997)
 $R_{RSC/NS}$ is the ratio of the service provide by RSC compared to reference systems (illustrated in Figure 6-5)

then the mean value of the examined services provided by RSCs through their first 15 years is estimated as \$20,500 (US 2014 dollars) per ha of RSC. However, this value may be as high as \$67,300 (US 2014 dollars) per ha of RSC (Table 6-8) based on the value range provided by Costanza et al. (1997). The lifespan of RSCs remains unknown, as these SCMs started being installed in 2000. However, they, like wetlands, are relatively self-sustaining, and with proper maintenance, should function more than 20 years (Shutes, 2001) for water quality and flow mitigation. These data used a chronosequence of 14 RSCs across MD and NC to better understand ecosystem service establishment in RSCs. The chronosequence available for this research is limited in application because of (1) the lack of data supporting the overall carbon budget, and (2) the relative newness of RSCs. Inlet/outlet carbon flows were not measured, carbon into the RSCs were unknown,

and depositional patterns were unique to each site due to the varying hydrologic conditions. Collecting more data, by establishing more RSCs, is needed for a more complete ecosystem services evaluation. As RSCs continue to be installed across the mid-Atlantic and Southeastern United States, more will be available for study.

Table 6-7 Literature valuation of ecosystem services in temperate forests and floodplain wetlands

<i>Ecosystem</i>	<i>Source</i>	<i>Location</i>	<i>1994 \$ ha-1 yr-1</i>	<i>2014 \$ ha-1 yr-1</i>	<i>Min</i>	<i>Max</i>	<i>Mean</i>
<i>Climate Regulation</i>							
Temperate Forest	Pearce and Moran (1994)	global	\$107	\$170.49			
	Adger et al. (1995)	Mexico	\$70	\$111.46	\$111	\$170	\$141
<i>Soil Formation</i>							
Temperate Forest	Pimentel et al. (1996)	global	\$10.00	\$15.98	\$15.98	\$15.98	\$15.98
<i>Biodiversity (Biological Control)</i>							
Temperate Forest	Pimentel et al. (1996)	global	\$4.00	\$6.39	\$6.39	\$6.39	\$6.39
<i>Habitat</i>							
Swamp	Pearce & Moran (1994)	USA	\$1,523.37	\$2,434.95			
	Pearce & Moran (1994)	UK	\$182.55	\$291.78			
	Gren & Soderqvist (1994)	Scotland	\$28.20	\$45.08	\$45.08	\$2,434.95	\$923.94
<i>Recreation</i>							
Swamp	Thibodeau & Ostro (1981)	USA	\$572.80	\$915.56			
	Gupta & Foster (1975)	USA	\$448.80	\$717.36			
Floodplain	Gren & Soderqvist (1994)	Australia	\$149.74	\$239.34			
	Lant & Roberts (1990)	USA	\$324.09	\$518.03			
	Gren & Soderqvist (1994)	Austria	\$1,948.65	\$3,114.72			
	Gren & Soderqvist (1994)	Austria	\$136.41	\$218.03			
Temperate Forest	Hanley (1989)	Scotland	\$187.64	\$299.92			
	Walsh et al. (1988)	US	\$65.73	\$105.07	\$105.07	\$3,114.72	\$766.01

Table 6-8 Valuation of select ecosystem services in RSCs based on minimum, maximum, and average values presented by Costanza et al. (1997) (Table 6-7).

RSC Age Category			
	0 to 4 yrs	5 to 9 yrs	10+ yrs
<i>Climate Regulation (\$ ha⁻¹ yr⁻¹)</i>			
Min	\$25	\$38	\$76
Max	\$38	\$58	\$116
Mean	\$31	\$48	\$96
<i>Soil Formation (\$ ha⁻¹ yr⁻¹)</i>			
Min	\$8	\$15	\$14
Max	\$8	\$15	\$14
Mean	\$8	\$15	\$14
<i>Biodiversity (\$ ha⁻¹ yr⁻¹)</i>			
Min	\$6	\$6	\$6
Max	\$6	\$6	\$6
Mean	\$6	\$6	\$6
<i>Habitat (\$ ha⁻¹ yr⁻¹)</i>			
Min	\$10	\$30	\$45
Max	\$536	\$1,631	\$2,435
Mean	\$203	\$619	\$924
<i>Recreation (\$ ha⁻¹ yr⁻¹)</i>			
Min	\$92	\$92	\$105
Max	\$2,741	\$674	\$3,115
Mean	\$4,611	\$674	\$766
Total (\$ ha⁻¹ yr⁻¹)			
Min	\$141	\$182	\$246
Max	\$3,328	\$2,385	\$5,686
Mean	\$4,860	\$1,363	\$1,806

6.6 Conclusion

Regenerative stormwater conveyance, like constructed stormwater wetlands, are SCMs underpinned by elements of natural ecosystems, thus providing more ecosystem services than conventional SCMs. The RSCs assessed in this research could provide up to \$67,300 per ha of ecosystem services for the first 15 years. Design strategies such as creating wet areas, planting rather than seeding, and incorporating recreational and educational infrastructure will improve the value of

RSCs. As urbanization has both directly and indirectly altered surrounding natural ecosystems, they are unable to provide ecosystem services to human beings to their fullest potential. An intervention proposed in the Millennium Ecosystem Assessment report (MEA 2005a) to curb ecosystem service degradation is the integration of ecosystem management into a broader developing framework. Designing stormwater infrastructure with more holistic objectives beyond just that of water quality and volume control may offer a constructive approach to restoring ecosystem services in urban areas.

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7. A Case for Designing Stormwater Nature Pockets in Children's Outdoor Spaces

7.1 Abstract

Urban areas require stormwater management. Recently there has been a movement towards decentralize, nature-based, green infrastructure approaches for managing stormwater. These systems have also demonstrated additional ecosystem benefits much needed in urban areas. At the same time, decades of research support the need for access to nature for healthy childhood development. Designing and locating nature-based stormwater systems where children frequent renders systems as multi-functional spaces, providing synergetic opportunities, which benefit individuals and communities. Challenges to integrating these spaces include safety, cost, and management, all of which can be overcome by smart and appropriate design. Such design requires collaboration between different skillsets and stakeholders through some minimal, but essential changes in the consultation and design process. Ultimately, integrating nature-based stormwater practices into children's outdoor spaces will provide economic, environmental, and social benefits to urban areas.

7.2 Introduction

The conversion of land from natural, often forested or grassed, cover to pavement and rooftops results in an increase of stormwater runoff. Stormwater runoff and associated pollutants are detrimental to surrounding ecosystems, and ultimately result in concerns over safety and public health (Curriero et al. 2001; Gaffield et al., 2003). As such, decentralized stormwater mitigation tools, such as low impact development (LID) and green infrastructure (GI), are required in new and retrofit development. LID and GI approaches often incorporate vegetation and other natural elements to mimic performance by natural ecosystems. Such nature-based stormwater systems may concomitantly provide other natural benefits, including, but not limited to, air quality regulation, habitat creation, and educational enrichment.

Natural areas provide many benefits to children. Research over the past thirty years has shown that contact with nature is critical for children's physical, cognitive, and social development, and, like a vitamin, should be taken in frequent doses (Kuo and Miller, 2013). At the same time, children's access to nature is becoming severely limited. In one generation, children's play has shifted from free, unstructured outdoor play to highly structured, often indoor play (Louv 2008, Planet Ark, 2011). Incorporating natural elements into common childhood settings, including schools, parks, and even childcare centers could provide more opportunities for children to interact with and benefit from nature.

Global efforts are being made to integrate decentralized stormwater tools into urban settings in creative and beneficial ways. Artful rainwater design (ARD) designs effective stormwater management techniques such that it also serves as an educational, recreational, and aesthetic asset (Echols and Pennypacker, 2008a). These designs focus on design aspects that allow for visual, auditory, tactile, or olfactory public interaction with stormwater (Echols and Pennypacker, 2008b). Despite successful implementations of many ARD and other stormwater projects with similar design goals throughout the USA, many are clustered in the northwest and few are designed or scaled specifically for child interaction.

Many of the sites that children frequent *do* require stormwater mitigation. Opportunities exist to extend the ecosystem benefits of decentralized LID/GI to also serve as nature pockets in children's play areas. This is particularly true in Southeastern USA, where population is projected to grow between 45% and 55% between 2000 and 2030, with 25% increase in children (US Census projection, 2006). The added need for new and retrofitted infrastructure from this population increase provides opportunities to rethink design goals and approaches, particularly in parks and schools. This paper explores the integration of stormwater mitigation objectives with those of childhood development by first, reviewing the stormwater

and ecosystem benefits of LID/GI; second, reviewing the need for nature in the daily lives of children; and third, discussing the challenges to integration. Actions and recommendations are also presented for realizing integrated, nature-based stormwater systems within childhood spaces. The paper concludes with three examples of stormwater integration into children's spaces, illustrating both the challenges and successes of the integration of uses. Ultimately, this integration is a healthy, cost-effective, and wise way to provide access to nature for our children.

7.3 Low Impact Development and Green Infrastructure

LID/GI are evolving tools within the stormwater mitigation field. These designs focus on detaining stormwater runoff, while promoting infiltration and evaporation such that site hydrology is not affected by the conversion from pervious to impervious surfaces (Coffman, 2000). These systems tend to be small, cost-effective landscape features that are integrated throughout a site. Often, LID/GI incorporates vegetation to encourage pollutant treatment processes and infiltration and evaporation, but ecological and social goals are often not considered in their design (Roesner and Brashear, 1999). Examples of LID/GI systems include bioretention cells (rain gardens), stormwater wetlands, and rainwater harvesting.

7.3.1 Bioretention Cells

Bioretention cells (BRC), also called rain gardens, are planted media beds designed to detain water, allowing time for media filtration, infiltration, and evapotranspiration (Figure 7-1). Typical BRCs are able to reduce total nitrogen (TN) and total phosphorus (TP) loads by at least 40% and 65%, respectively (Davis et al., 2006; Hunt et al., 2006; Davis, 2007), while also, on average, reducing runoff volume and peak flow by 90% and 60%, respectively (Hunt et al., 2006; Davis, 2008). BRC increase in performance when designed with a saturated zone at the bottom of the media (Brown and Hunt, 2011).



Figure 7-1 Children playing in a terraced bioretention system at the North Carolina Museum of Art in Raleigh, North Carolina (NC), USA (photo by Bill Hunt, NCSU)

7.3.2 Stormwater Wetlands

Stormwater wetlands are shallow ponded, highly vegetated systems used to capture runoff and slowly release it over time. They offer natural filtration and slow water down so that pollutants are removed via sedimentation, adsorption, and biological processes. Wetlands are effective at reducing pollutants due to regions of varying water depth (Figure 7-2). Stormwater wetlands can achieve 70% to 85% reduction in total suspended solids (TSS), 50% to 60% in TP, and 25% to 50% in TN (Cappiella et al., 2008; Lenhart and Hunt, 2011). Volume and peak flows are reduced by 50% and 95%, respectively (Lenhart and Hunt, 2011). Wetlands are generally used for larger watersheds, such as those greater than 4 acres (Wossink and Hunt, 2003).



Figure 7-2 This wetland at SAS Institute Preschool in Cary, NC receives water from shed rooftop shown in top-right corner of the photo (photo courtesy of Natural Learning Initiative)

7.3.3 Rainwater Harvesting

Rainwater harvesting (RWH) is traditionally installed in arid and semi-arid climates, but has expanded in application due to recent droughts in the Southeastern United States. RWH is used to capture stormwater from rooftops and store it for future usage (Figure 7-3). Often, RWH must have designated annual usage to be permitted as a stormwater mitigation tool. However, innovative designs, which slowly release unused rainwater, allowing adequate storage for upcoming storm events, are being explored (DeBusk, 2013). In addition to the volume reduction through water reuse, RWH can achieve some pollutant reductions within the tanks (DeBusk and Hunt, 2013).



(a)



(b)

Figure 7-3 Rainwater harvesting systems provide water play and education at (a) the Munchkin Academy in Buxton, NC (photo courtesy of Natural Learning Initiative), and (b) White Deer Park in Garner, NC

7.3.4 Ecosystem Services in LID/GI

LID/GI systems, with the exception of RWH, function by mimicking natural ecosystem processes to provide stormwater mitigation benefits. For example, vegetated systems are able to reduce runoff more than non-vegetated systems because plants use the water for photosynthesis. Plant roots support microbial communities which transform nutrient pollutants to less mobile forms. Earthworms have even been shown to decrease clogging of BRC media, expanding the life span of the system (Greene et al., 2009). The natural processes occurring in LID/GI systems perform better as stormwater control measures than conventional engineered systems (Wilson, 2013; Moore and Hunt, 2012; Chapter 6).

Ecosystem services are benefits that humans derive from nature (MEA, 2005). Folk et al. (1998) found that large cities across Europe depend on land area 500 to 1200 times greater than the city themselves to function. In addition to increased stormwater mitigation performance, studies have pointed towards additional ecosystem services of nature-based LID/GI (Table 7-1). The presence of vegetation in a BRC or wetland reduces local temperature through evapotranspiration (Streiling and Matzarakis, 2003; Bolund and Hunhammar, 2007). Stormwater wetlands are able to sequester carbon (Moore and Hunt, 2012). Trees present in a BRC can reduce air pollutants and process carbon dioxide (McPhearson et al., 1997; Taylor et al., 1998). Urban gardens are able to provide habitat for birds, bees, and other important fauna (Daniels and Kirckpatrick, 2006; Fetridge et al., 2008; Sperling and Lortie, 2011). Although RWH does not include vegetation itself, it supports natural processes by providing us with an opportunity to recycle nutrient pollution from stormwater runoff to support plant growth via irrigation. Also, these systems reduce energy demands by keeping water sources localized instead of requiring pumping to places of use (Daigger, 2009).

Table 7-1 Benefits of specific LID/GI strategies

LID/GI	Benefits for Children	Additional Ecosystem Services
Bioretention (BRC)/ Rain	<ul style="list-style-type: none"> • Learn, see, understand hydrologic cycle • Connects people actions with environmental consequences • Create sense of water sustainability • Fosters environmental awareness • Science, writing, art curriculum development • Opportunities for unstructured exploration • Diversity of sensory stimulation • Learning plants and ecosystems through seasonal, life-cycle changes 	<ul style="list-style-type: none"> • Reduces peak stormwater flows • Recharges groundwater table • Microclimate regulation and reduction in urban heat island • Provides habitat for beneficial species • Attracts pollinators • Opportunity for increasing biodiversity • Reduces nutrients and metals in rainwater • Improve air quality • Promote seed propagation • Opportunity for food production
Wetlands	<ul style="list-style-type: none"> • Incorporates all nature's ingredients (i.e., sun, rain, bugs, birds) • Naming and categorizing species • Develop a sense of familiarity and pride related to outdoor environments • Fosters positive and cooperative relationships with others • Promotes inclusion • Promotes creative play 	<ul style="list-style-type: none"> • Critical to carbon cycling • Reduce microbial pollution • Manage stormwater pollution • Reduce runoff flow and volume • Provide flood mitigation • Regulate microclimate • Improve air quality • Provide opportunity for food and resource production • Provide habitat for beneficial species • Source of biodiversity
Rainwater Harvesting (RWH)	<ul style="list-style-type: none"> • Science, writing, mathematics, and art curriculum development • Demonstrates important concepts like water cycle, water resource conservation, etc. • Hands on water play • Sense of local, environmental context (use water onsite) • Foster positive and cooperative relationships with others • Promotes inclusion • Promotes creative play • Fosters environmental awareness 	<ul style="list-style-type: none"> • Opportunity for energy savings when water is reused • Nutrients in reuse water may reduce need for additional soil amendments when used for irrigation • Uses the more appropriate resource of non-potable water in place of potable water

Traditionally, stormwater features are placed peripherally and out of the way such that some services are not actualized. Limited research exists evaluating ecosystem services of stormwater systems (Moore and Hunt, 2012; Chapter 6), likely because many services are difficult to quantify. On the other hand, research is continuously published from the perspectives of many disciplines on the need for natural spaces accessible to children, particularly in urban settings (Matsuoka and Sullivan, 2011). Decentralized LID/GI may be one way of bringing pockets of functioning ecosystems into children's spaces (Table 7-1)

7.4 Children in Nature

7.4.1 Importance of Child Play in Nature

Children have an innate connection with nature. Kaplan and Kaplan (1973) discuss the importance of nature for cognitive respite. E.O. Wilson (1984), in his theory of *Biophilia*, claims that people subconsciously find security in nature. Whatever the theory, children universally seek out dirt, water, and natural elements (Moore and Wong, 1997; Blair, 2010). Nature also provides abundant benefits that are important to healthy child development. When outdoors, multiple senses are softly stimulated by nature, in a way that is both restorative (Kaplan, 1995) and experiential (Blair, 2000). Children's engagement with nature changes over time, both seasonally and physically (plant an acorn, climb the adult oak), offering variety to their educational experiences. Nature allows children to interact with it and within it in a variety of ways (Moore, 1996; Letser and Maudsley, 2007). For example, a tree can afford activities such as climbing, resting in the shade, collecting loose parts, growing food, chasing around, and etcetera. Such experiences with nature are not only fun for a child, but provide meaningful learning interactions essential for childhood development.

Cognitive development improves when children have contact with nature. Wells (2000) observed improvement in the ability to focus when urban children were

relocated to areas in more natural settings. Kuo and Taylor (2004) have also reported improved Attention Deficit Hyperactivity Disorder (ADHD) symptoms when children have performed an activity in natural areas. When nature is incorporated into classrooms, schools have reported observable and measurable improvements in classroom performance (Harvey, 1989; Lieberman and Hoody, 1998; AIR, 2005; Blair, 2010; Matsuoka, 2010).

Several studies have linked outdoor play to physical health. Grahn et al. (1997) (as described in Moore and Cooper Marcus, 2008) showed that children who played in wooded outdoors areas of their preschool exhibited advanced gross motor skills, higher fitness levels, and lower sickness rates than their traditional school counterparts. Liu et al. (2007) found vegetation around a child's house to be predictive of a healthy weight in children living in dense neighborhoods. These interesting correlations may be related to the attractiveness of the natural world to children. Vegetative areas are likely more attractive for outdoor play than expansive concrete surfaces present in many schoolyards.

Recently, the medical field has acknowledged the health values of exposure to nature. Dr. Howard Frumkin, Dean of the School of Public Health at the University of Washington and former director at the U.S. Center for Disease Control (CDC), calls his field to action, using nature conservation as a public health strategy to disease prevention (Frumkin and Louv, 2012). In late 2013, the American Public Health Association adopted Policy Statement 20137, which "Calls on public health, medical and other health professionals to raise awareness among patients and the public at-large about the health benefits of spending time in nature and of nature-based play and recreation," and "promote[s] natural landscaping," thus emphasizing further the essential need for childhood access to nature.

Contact with nature also improves children's social behavior. Teachers have reported increased self-esteem, improved behavior, and more positive peer after students with increased access to nature (AIR, 2005; Dymont, 2005). The incorporation of trees and plant patches offered different spaces for the children so that they could have small group or personal space. One teacher in Toronto commented that Special Education students found a space in an area of shade trees where they were comfortable and accepted by other kids.

Additionally, children raised in frequent contact with nature grow up to be more environmentally conscious. Thompson et al. (2007) found that frequent childhood visits to wooded areas or green space correlated to increased frequency of adult visits. When children are exposed to nature, they are also more able to see the interconnectedness of the world (Dymont, 2005), which in turn, will bring a new perspective to human interaction with nature—the soil grows the plant, I eat the plant, I compost the scraps, the scraps nourish the soil. On the other hand, if children miss exposure to the natural world, they may lose their bond with nature as adults (Hansen, 1998), which could be detrimental to the human relationship with the natural environment. Ultimately, Rivkin (1997) states that knowing nature will lead to caring for nature. Caring for nature, in turn, is a keystone for stewardship behavior in adulthood (Chawla 1999; Chawla, 2006). Thus, raising our children to give nature a voice is critical to the future of innovative approaches to support our increasingly urban populations.

7.4.2 Water and Childhood Development

Water plays a particularly important role in childhood development. First and foremost, people are attracted to water (Kaltenborn and Bjerke, 2002), and this is true particularly for children (Moore and Wong, 1997; Blair, 2010). Interaction with water is often relaxing and calming (Frost et al., 2004), but can also be intriguing and stimulating (Hendrick, 1998). Water play allows children to experiment with mathematical concepts, such as more/less or empty/full (Crosser, 1994). A rainstorm

may fill up a pond that was previously empty. Or a child may find that pouring a large bucket into a smaller bucket results in overflow. When water is experienced in nature, children can observe and learn about science concepts like the water cycle, rain, and mud (James and Granovetter, 1987). They can also observe gravity as water flows from high places to low places or the different phase of water between summer dry spells and winter ice spells. Physical development improves when children navigate water play areas, such as hopping stones and dodging puddles. Sensory experiences are widened when children touch (or step in) different textures (squishy, wet, or slimy) and temperatures (cold, warm) (Hendrick, 1998). Socially, water can be the center of cooperative learning and play, with common exploration of wet environments and sharing of toys and tools. Children observe water everywhere (from faucets to puddles). When they are presented with an intimate opportunity to observe water in a natural setting, children will make connections to the water they use for drinking, showering, or even flushing the toilet. Water conscious children are likely to become water conscious adults (Chawla 1999; Chawla, 2006), much needed for innovative solutions as natural water resources continue to become scarce (US EPA, 2014).

7.4.3 Children's Access to Nature

Children have increasingly less access to nature. Many studies have attempted to articulate the causes of limited access. Cultural changes have occurred in the past 30 years, including a reduction in children's independent range related to parent's concerns for their child's safety (Lester and Maudsley, 2007). This may be related to an increase in media depicting dangers, increased traffic, and less community interaction within neighborhoods. Additionally, children's schedules are more and more structured, hindering free play and exploration (Johnson, 2000; Lester and Maudsley, 2007). With increased access to technologies, play is more sedentary and technology-based (Lester and Maudsley, 2007).

When children do have access and time for playing outside, artificial play structures, open green fields, and asphalt jungles can dominate their play spaces. For instance, a baseline assessment of childcare centers in North Carolina showed three times as many manufactured components as natural components within the outdoor play areas (Moore and Cooper Marcus, 2008). It is a common misconception that if you pay a lot of money for a play structure, the quality of play will also be more valuable.

Ironically, sustainable development has focused intently on technology and the buildings themselves, and very little on the outdoor space surrounding the buildings. Rating systems have only recently been geared towards the quality of outdoor spaces (i.e., Sustainable Sites Initiative™ (SITES™) and Envision™). Conventionally, most outdoor space, when referenced, is categorized as “green space”. However, not all green space is equal. Although closer to nature than concrete, open grass patches can hardly be considered a functioning ecosystem. Gardens, trees, and water all contribute to the biodiversity of a space and, therefore, are requisite to achieve the multi-benefit potential of a functional ecosystem.

There have been global movements towards incorporating multi-functional nature pockets in urban and suburban areas across the globe (Hoyer et al., 2011). Although these pockets can serve as models for proliferating and fine-tuning integrated design of LID/GI in children’s spaces, few consider childhood access beyond that of safety (which is important). Designing spaces accessible and useable for children requires a different perspective and different scale (NLI, 2010a; NLI, 2010b; Moore, 1996). For example, children prefer nooks to open spaces, or enjoy pavers that encourage hopping or jumping. To optimize the value of such integrated artful rainwater design in children’s spaces, they need to be designed with children in mind.

7.5 LID/GI as Nature Pockets

The benefits of childhood contact with nature, particularly water in nature, are thoroughly documented, as well as the consequences of childhoods without. The medical, educational, ecological, and public health fields agree that children need to be in contact with nature. Nature is Vitamin G (Kuo and Miller, 2013), and it should be experienced via different exposure routes (viewing from a distance to digging in the dirt). It should be taken in regular, frequent doses. And you need to have access to it to receive benefits from it. Therefore, nature should be prevalent in places where children frequent—parks, childcare facilities, and schools.

Decentralized nature-based stormwater practices, like LID/GI, when integrated into children’s outdoor play spaces and designed with accessibility for children, offer opportunities for children-nature interaction. Many places children frequent have impervious surfaces and required stormwater control measures. Using stormwater systems to serve needs beyond that of stormwater mitigation is an example of “functional integration” (Fox, 2009), where once space is able to provide multiple functions. Stormwater mitigation needs are met, while while also providing an outdoor classroom where children learn about hydrology, horticulture, and biology, and play area where children can hop puddles or hide behind sedges. These multi-functioning landscapes can offer economic, environmental, and social value at very little cost beyond our conventional landscapes (Table 7-1).

7.5.1 Challenges to Integration

Designing integrated LID/GI systems into play and learning environments for children has to overcome multiple challenges. LID/GI systems are only now becoming standard tools in the engineering toolbox. These systems require some more design integration, require more upfront cost, and require collaboration outside of the traditional engineering disciplines. On the other hand, child outdoor learning environments continue to be designed using manufactured play equipment in

spaces of very little landscape diversity. The integration of these two concepts has unique challenges including safety concerns, cost, and management.

7.5.1.1 Safety Concerns

Several misconceptions exist about the integration of nature into children's spaces—some merely perceived and some requiring careful consideration. Toxin exposure has been the impetus to many regulations restricting childhood environmental exposure. Frumkin (2001) argues that the positive health effects of exposure to nature often far outweigh the negative effects. LID/GI systems are designed to retain pollutants, and as such, should be designed appropriately for the space. Woodchips, for example play an important role removing metals and hydrocarbons in BRCs. Therefore, BRCs in childcare centers with very young children may consume the mulch should not receive runoff from pavement with heavy vehicle traffic (Brown and Peake, 2006). Or, a series of small systems could be designed where children have access to the downstream systems where water has already undergone treatment.

Most stormwater systems will, at some point, have ponding. In most cases, this will only occur during a rain event. In stormwater wetlands, the ponding is intended to be permanent. Standing water in children's spaces is often viewed as a drowning hazard, and therefore prohibited. Access to permanently ponded water could be a safety concern where very young children are playing, such as childcare centers. In these cases, flexibility in the maximum depth of the wetland may overcome this concern while maintaining some stormwater benefits (see Figure 7-1 above). When the credited minimum depth of 18" is used for the deepest parts of wetlands, wetlands should not pose concern at parks or elementary schools. Successful alternatives to designing deep retention structures include spreading the water into multiple shallower ponds (Echols and Pennypacker, 2008a; Echols and Pennypacker, 2008b). Regulatory restrictions to shallow ponded LID/GI are likely due to conservative risk management (Moore and Cooper Marcus, 2008), ignoring

the many benefits of such systems. Successful applications of ponded LID/GI within children's environments do exist. One example is Harry K. Hamilton Elementary School in Nova Scotia, who restored a stagnant pond into a thriving amphibian habitat (Evergreen, 2001). The pond only needed to be 18" deep for a functional habitat, and parents and stakeholders were comfortable with this depth.

Natural areas such as vegetated LID/GI provides habitat to a variety of plant and animal species that live side by side. Snakes and spiders are essential to keeping the system in check so that other creatures do not overrun a system and deteriorating its ecosystem function. Some predators, such as snakes or wasps, may be viewed as dangerous when located in or near children's play spaces, but this is often a misconception based on our lack of knowledge about the ecosystem. As opposed to the "fear of the unknown," the presence of these creatures within their own habitat can offer a learning opportunity for children to develop healthy interaction skills to foster cohabitation. In many cases, the presences of habitat for such critters can be a much safer alternative to spraying chemically-based pest controls or poisons to regulate other unwanted pests. First Environments, a childcare center in Durham, North Carolina, reported less fire ant activity when they restored their outdoor space to have more natural diversity (personal communication, October 9, 2012). Additionally, decentralized LID/GI does not have to be a chaotic, wild environment to provide childhood benefits. BRCs or rainwater harvesting can be designed to incorporate elements of nature in a very controlled setting, which may be more attractive to potential stakeholders.

7.5.1.2 Cost

Cost is often a deterrent in considering naturalization. Although nature-based stormwater systems tend to have higher upfront cost, their long-term benefits often result in less expensive net costs (Wossink and Hunt, 2003). This is also likely the case with natural outdoor spaces, especially when considering the costs of healthcare alone, although no study yet exists to demonstrate this. When the two

objectives are integrated—using LID/GI as a pocket of nature—the net cost may be even less due to resource integration (Fox, 2009). Multifunctional spaces, such as these, reduce the need for individual spaces for each unique need. This may reduce overall land needs, but also overall management costs. Furthermore, well designed and cared for elements of nature will likely increase the quality of education for children, and make the school and ultimately neighborhood more desirable and valuable. It is important for stakeholders to understand the holistic benefits of investing in such systems, and this may be helped by policy recommendations, such as the Energy Independence and Security Act, requiring federal development greater than 0.5 ac to use LID/GI verses conventional stormwater (EISA, 2007). As a result, nature-based stormwater systems are already being implemented on federal lands.

7.5.1.3 Management

The success of a landscape depends heavily on its management (Brink and Yost, 2004). Urban vegetation is often very ordered and manicured through trimming, weeding, spraying, and mowing. The management of natural areas, especially areas designed to treat stormwater and be accessed by children, require holey different management practices. It is important to allow for some natural order (sometimes perceived as chaos) in the system to allow the system to be functional as a nature pocket. Many people who care for landscapes will not inherently know how to do this, and it is important to articulate what things should and should not be done. For example, do not spray pesticides or herbicides as they impair water quality and are harmful to children. Instead, hand weed when plants are young (an activity that can be incorporated into a lesson or child’s activity). In the end, natural systems will likely require less frequent care, if they are designed well and nurtured through establishment (Brink and Yost, 2004).

7.5.1.4 Summary of Challenges

Some challenges may be more difficult to overcome than others. Many of the challenges stem from lack of experience or misconceptions. Accessible and interactive LID/GI is not regularly seen in childhood play spaces, so each stakeholder has their own perceptions and prejudices. Engineers and planners often underestimate LID/GI functionality, such that these systems are often designed with the sole purpose of stormwater mitigation. Educators have little exposure to such systems, and are often not sure how to incorporate them into classrooms and lessons. Designers are trained to cue the public as to how to interact with their environment by translating the space into the cultural language (Nassauer, 1995), but this is often not done on a child-scale. Each challenge that arises should be carefully considered. Active stakeholder participation is essential in understanding and addressing each of the challenges, and the others that will arise as more LID/GI are installed in child play spaces.

7.5.2 Actions and Recommendations

As engineers, landscape architects, ecologists, gardeners, etc., it is often difficult to think beyond the design objectives that we are paid and trained to address. However, addressing multiple programmatic and functional objectives creates synergistic opportunities to benefit individuals, groups and organizations, and communities-at-large. Papers written on naturalizing children's spaces unanimously call for collaboration between skillsets and stakeholders (Johnson, 2000; Johnson and Hurley, 2002; Brink and Yost, 2004; Dymont, 2005; Moore and Cooper Marcus, 2008; Blair, 2010). The case of creating LID/GI as nature pockets in childhood play spaces is no different. Engineers should discuss the potential placement of LID/GI systems such that they become the focal points of outdoor spaces. They should call upon their horticulture colleagues to help choose site appropriate plants for their systems. They should work closely with their landscape architecture colleagues to organize the site in ways that maximize programmatic function and choreograph the interaction(s) between people and the system(s). They should work with public

health officials to understand what pollutants should be a concern for children. Educators and child development experts should provide insight into scaling of stepping-stones, benches, access points to optimize accessibility and functionality of the site for children. The logistics of these collaborations are currently difficult, as our contracting structure is designed such that each of the colleagues is located in different specialized offices. Despite this, the consulting process can be proactively organized to facilitate collaboration. First, developing a well-articulated design vision (concept) and project goals (intent) will help to identify disciplinary overlaps and to synthesize project outcomes into a seamless, integrated whole. A rating system, such as Sustainable Sites Initiative™ or Envision™, can be used to help provide guidelines and examples for integrating goals. Second, any professional should know their own skills and expertise, and pursue contacts with different skills and expertise. When you have “go-to” experts, collaboration becomes a very natural part of design. Third, instead of a compartmentalized, step-by-step design process, consider the design as a more iterative process. All the disciplines should be involved for each phase of the project, such that each has a stake in the design as a whole. Ultimately, as more companies design multi-functional spaces by collaboration, the more multi-functional spaces will be built.

7.6 Examples of LID/GI in Children’s Play Space

As this concept becomes more accepted, it is important to share the successful stories, as well as the stories that offer opportunities for learning. Several of these integrated systems already exist, and much can be gleaned from them.

7.6.1 Sidwell Friends School in Washington, D.C.

Sidwell Friends School is the epitome of integrated water, energy, and education design. Located in the affluent, the historic Tenleytown, Washington, D.C., the school has 15-ac of land to use as its classroom. Apart from a terraced-wetland-treated wastewater reuse system, the newly renovated middle school (2007) captures its stormwater in vegetated swales, directing it into a courtyard rain garden

and habitat pond. The habitat pond serves as an outdoor classroom, hosting scientific experiments comparing water quality from inflow and outflow samples, and lessons on the connectedness of ecological systems, waste conservation, and water purification. A greenroof also reduces overall runoff through evapotranspiration, while serving as a vegetable garden and laboratory for the middle school. The green roof, rain gardens and pond contain 50 native plant species and provide habitat for endangered species such as the Snowy Owl and Monarch Butterfly.

7.6.2 First Environments Childcare Center in Research Triangle Park, NC

First Environments Childcare Center in Durham, NC provides a hopeful model for the integration of LID/GI in outdoor spaces for pre-school children. The space just outside the building includes BRC capturing runoff from one roof, and raised garden beds watered by captured rainwater. Children learn about water as a resource, and the role of rainwater in replenishing our groundwater and nourishing our plants. They complete the lesson by eating snacks and lunch from their garden. First Environments is constantly improving their outdoor space, choosing one or two small projects at a time. Families, children, and staff play a large roll in managing the space through suggesting and refining ideas, and workdays. The site shows that with the motivation and hard work of a community of people, the integration of RWH, BRC, as well as many other pockets of nature can be integrated into not only childhood spaces, but more importantly into the lived experience of childhood.

7.6.3 The Montessori School of Winston-Salem, NC

The Montessori School of Winston-Salem serves as an illustration of the different stakeholder challenges of integrating LID/GI into childhood spaces. The school had a stormwater dry pond on its grounds. Over time, the pond outlet structure became clogged, thus causing permanently ponded water. Eventually, a shallow wetland environment began to form. The wetland became a part of the school's outdoor classroom, with students exploring and learning about the ecosystem. The school was later informed that converting the system back into a dry pond via unclogging of

the outlet structure was required per the regulations. The dry pond area, again, became a single-function space, no longer a place of student interaction. It is easy to understand the need for onsite stormwater mitigation. But, in practice, dry ponds offer few pollutant removal benefits compared to wetlands (Lenhart and Hunt, 2011; Wilson, 2013) and very few additional ecosystem benefits. It would have been interesting to investigate what sort of stormwater benefits were being achieved by the wetland, and to consider how the benefits may outweigh the loss in storage volume. However, it was not in a stormwater regulator's skillset, mindset, or prerogative to do this. This example illustrates the value and potential of nature-based stormwater systems are to childhood spaces, but also the consequences of out-of-date regulation and professional practice that focus solely on single-purpose systems. Another lesson from this site is the ease at which conventional stormwater system located in parks and schools can be converted to thriving natural outdoor classrooms. It is imperative, though, for all stakeholders to be involved, such that stormwater and childhood development goals are met.

7.7 Conclusions

Nature is invaluable. Research quantifying and valuating the benefits of integrating nature into engineering designs has demonstrated a value greater than that of any manmade market. Similarly, decades of research on childhood contact with nature shows us that this interaction is essential for childhood development. It is prudent, then, to consider how to optimize the services that nature freely offers us through the wise design and arrangement of space. Nature-based stormwater systems, like LID/GI, should be located where and designed so that children have access to play, explore, and enjoy them. Initially, the vision of integrating stormwater systems and children's play spaces into unified amenities may pose challenges, but smart, appropriate design, achieved through the interdisciplinary efforts of many different fields, allows the benefits to far outweigh the costs. Ultimately, these multifunctioning

nature pockets offer economic, environmental, and social value needed to sustain our urban and suburban societies.

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8. Recommendations for Future Research

This research provides an important foundation in understanding of RSC stormwater mitigation performance and ecosystem service provision. In terms of hydrology, four important runoff fates were identified – treated surface flow, seepage, evapotranspiration, and exfiltration. Seepage composed the largest fraction of the RSC discharge hydrograph, and evapotranspiration, the smallest. In all North Carolina RSCs studied herein, little to no vegetation was established during the monitoring period, which likely contributed to the low exfiltration rates. Further research on planted (rather than seeded) RSCs or RSCs with further established vegetation is necessary to better quantify evapotranspiration potential. Additionally, evapotranspiration will likely occur at higher rates when water is retained in cells (i.e. exfiltration trenches), than in well-drained systems. The additional fraction of evapotranspired runoff due to vegetation and retention is unknown, and may or may not be significant to the water balance as a whole. Increases in the fraction of evapotranspired water within an RSC will result in decreases in water previously fated as surface flow, seepage, or exfiltration. It is likely that seepage could be primarily affected by this, as evapotranspired water will be that which is present in the media to be taken up by plant root systems. Another way to further reduced runoff volume that was explored in this research was using retention strategies to increase exfiltration. However, the RSCs studied herein demonstrated a corresponding *increase* in surface flow as ponded water reduced the available subsurface storage. There is the possibility that if more established vegetation were present for the purpose of increasing evapotranspiration, the water stored in the media is more likely to be decreased more quickly between storm events, allowing more subsurface storage when runoff enters the RSC. Ultimately, the role of vegetation and retention on evapotranspiration on RSCs needs to be quantified to provide the most accurate water balance in well-established RSCs.

Another important hydrologic question that came up as a result of this research is the role of groundwater interactions in both the hydrologic and water quality performance of RSCs. The Brunswick County RSC (Chapter 3) demonstrated that replacing an eroded swale or channel with an RSC may, in fact, raise the local groundwater table, such that groundwater/stormwater interactions occur. The presence of groundwater in the Brunswick RSC increased surface flow during large storm events and restricted loss via exfiltration. Despite this, most of the flow through the RSC left as seepage, although the fraction of seepage attributed to treated runoff versus groundwater remains unknown. Incorporating multiple groundwater wells, located along both sides of the entire length of the RSC would provide enough groundwater temperature data to perform a temperature mass balance and discretize the two sources. Understanding the amount of groundwater leaving as seepage during a storm event is also important in determining the extent to which RSCs can mimic all predevelopment pathways, but distinguishing between event (runoff) and pre-event (groundwater/stored runoff) outflow. Evidence from the Alamance site (Chapter 4) suggests that RSCs can mimic all pathways, but only statistically significant data can further verify this.

RSC hydrologic analysis from this data provided enough information to build an early version RSC hydrologic performance model (Appendix A). The model allows some flexibility in design (i.e., number of cells, geometry of cells), but considers only well-drained RSCs. Model media seepage rates were estimated from the Alamance RSC (Chapter 4) only, as a seasonally high groundwater table at the Brunswick RSC (Chapter 3) made this data unusable for the model. The model was tested using surface flow producing events at the Alamance RSC, with the model continuously estimating higher surface flows than observed in the field. It was estimated that variances between model and actual results were primarily attributed to the monitoring weirs at the Alamance site restricting surface flow. Therefore, validation of the model for unmonitored RSCs, under varying hydrologic conditions will require

further research on a variety of other RSC designs. Furthermore, future RSC monitoring for this purpose should not include inter-system monitoring weirs that potentially restrict flow compared to unmonitored RSCs. It is expected that the model provided by this research will be adjusted as more data is available.

Several further research questions arose from the water quality analysis in this research. First, ponded conditions are likely to also affect RSC water quality performance. Research at the Lake Wheeler site (Chapter 5) showed that pollutant loads in seepage leaving RSCs can be higher than loadings from surface flows leaving an RSC. At present, the only research known to this author on subsurface water quality within RSCs is presented herein (Chapter 5), and that being limited to nitrogen from artificial storm events through a well-drained RSC in the winter. More research is needed to expand this evaluation to include multiple pollutants (i.e., TSS, nitrogen, phosphorus) under varying hydrologic conditions (i.e., seasonal ponding, groundwater interactions, exfiltration trenches, well-drained) during different seasons (i.e., summer, fall, winter, spring). It is expected that the conditions studied at Lake Wheeler exist in many RSCs, but also demonstrate the worst case scenario. Wetter hydrologic conditions during warmer seasons with vibrant plant growth will likely contribute to an increase in biological nutrient transformations, further reducing nitrogen in seepage. Wet conditions, on the other hand, may mobilize phosphorus and lead to an increase in phosphorus loadings. Plant uptake may contribute to decreased pollutant loadings in warmer weather, but seasonal vegetative die-of may increase nutrient loads in during colder seasons. Subsurface pollutant responses to these varying conditions remains un-researched, but very important, as seepage will ultimately enter receiving waters.

The presence of established vegetation in ponded RSC is expected to increase pollutant loadings in surface flows as well. Previous research on wetland-like RSCs has demonstrated greater nutrient reductions between surface inflow and outflow

(Browning, 2008), where well-drained RSCs provided very little nutrient reduction (Filoso, 2013). The Alamance RSC (Chapter 4) showed some significant nitrogen and phosphorus reductions, but not in the wetland-like portion of the RSC, as expected. As pointed out in the discussion portion of Chapter 4, it is hypothesized that the lack of established vegetation in the wetland-like portion of the RSC resulted in its inability to further remove nutrients. Therefore, to get an accurate prediction of surface water quality performance in seasonally-ponded established RSC, further research on water quality performance in planted (rather than seeded) RSCs or RSCs with further established vegetation under these hydrologic conditions.

This research also showed that RSCs are able to provide a suite of additional ecosystem benefits in urban areas, beyond that of just stormwater mitigation (Chapter 6). For most of the benefits studied (i.e. carbon sequestration, biodiversity), RSCs performed as well as constructed stormwater wetlands (CSW). However, ecosystem analysis was limited to nine RSC sites across, primarily in Maryland (MD), and most of which were less than 5 years old, and all but one less than 10 years old. The limited amount of data available for older sites affected the ability of this research to accurately project ecosystem benefits, primarily related to soil formation (i.e. carbon sequestration, microbial biomass). It is expected that, as current RSC age and as more RSCs are built, more accurate projections will show a slower rate of soil carbon accumulation, and deeper penetration of carbon in the soil, verifying RSC potential as long-term carbon sinks. This research also suggested some possible confounding characteristics that may affect ecosystem performance more than age (i.e. Hydrologic conditions in RSCs, watershed imperviousness). It is expected that habitat potential, recreation, and education will be affected by these factors. Habitat is strongly related to natural space and connectivity. Recreation and education appear to be more appealing when water is present, and available when located in proximity of people. Future ecosystem assessments should seriously consider these characteristics and ensure that they are evenly distributed across the

chronosequence. In this way, such the effect of such confounding can accurately be examined.

This research also presents an argument for incorporating nature-based SCMs, including RSCs, into childhood play spaces. The article presents several challenges including safety, cost, and management. Safety concerns include both exposure to pollutants and risk of drowning. Further research is needed in characterizing runoff pollutants of concern (i.e., fecal bacteria and heavy metals) from varying urban landscapes, including parks and school grounds, as well as the safety threat these may provide to children. Research should be conducted on the effect of ponding depth of wetlands on stormwater mitigation performance, as such SCMs may need to be adjusted to meet safety regulations on school grounds. Beyond SCM performance, rigorous economic ecosystem service analysis, should be conducted on nature-based SCMs in childhood play spaces to help promote the valued benefit of these systems beyond their up front price-tags. Ultimately, stigmas against incorporating nature-based SCMs into childhood spaces can only be overcome by experience. Whenever possible, field-based research should include building such sites in public settings, where people will become more familiar, and possibly even value, the SCM nature pockets.

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Appendix

A. Appendix: Introduction and User Manual for RSC Hydrology Performance Model

Using the Model

a. “Watershed” Tab (blue)

Selection of the blue tab labeled “Watershed” should result in the following screen, with varying values in the cells (Figure A-1). Blue cells are model user inputs. Red cells are determined based on the inputs and may be useful to know. The model user should not adjust red cells.

	A	B	C	D	E	F	G	H
1								
2	Watershed Characteristics							
3								
4			Project Location =	Piedmont				
5								
6			Watershed Area (A) =	4 ac				
7			HSG =	D				
8								
9			C,comp =	0.9				
10			CN,comp =	90				
11			Tc =	10 min				
12								
13								
14								
15	Precipitation Characteristics							
16								
17			Precipitaion Depth =	1 in				
18			Precipitation Intensity =	1 in/hr				
19								
20			S =	1.1				
21			Q =	0.3 in				
22			Runoff Volume =	4650 cf				
23								
24			Peak Flow =	3.6 cfs				

Figure A-1 Screen shot of blue “Watershed” tab

i. Inputs

Watershed Characteristics

- *Project Location* – Model designed for sites in North Carolina, located in the Coastal Plains, Piedmont, or Mountain per Figure A-2.

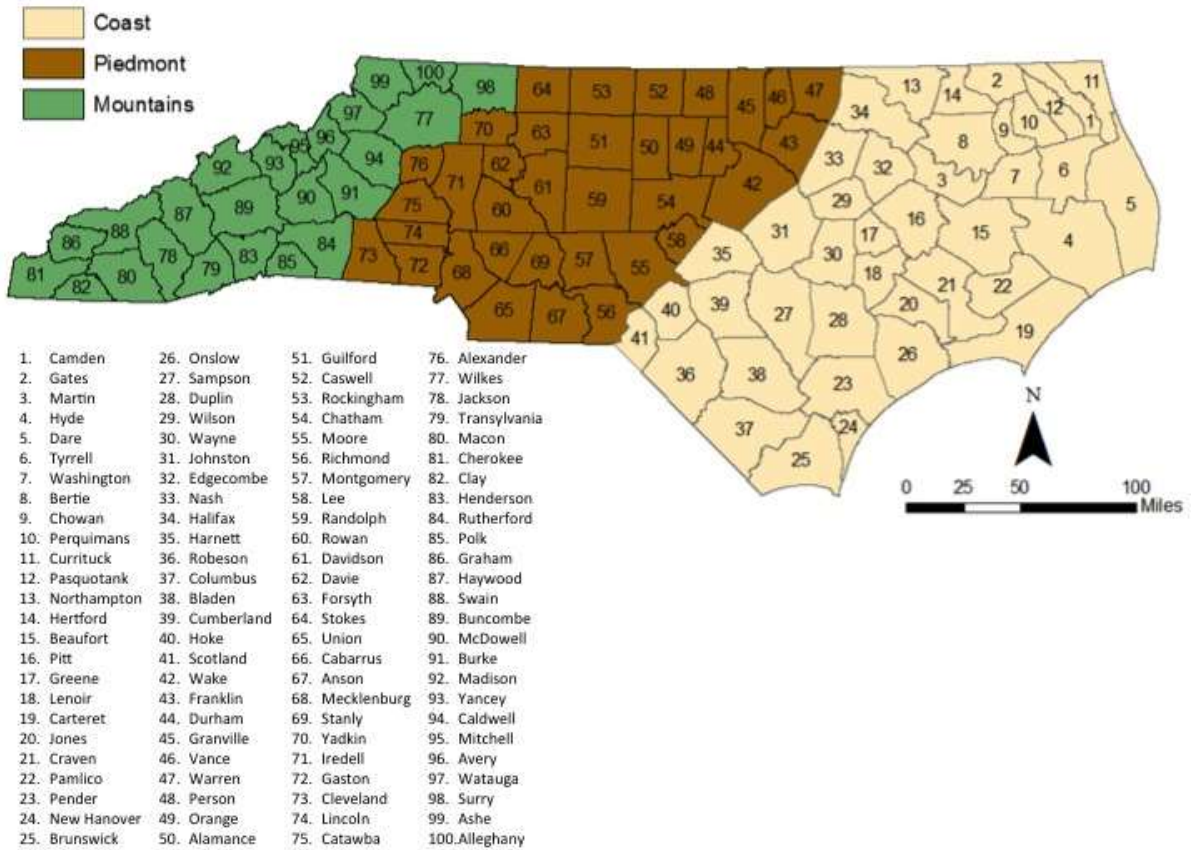


Figure A-2 North Carolina counties by ecoregion

- *Watershed Area* – Total area of contributing watershed to the point where RSC will discharge, in acres
- *Hydrologic Soil Group (HSG)* – Classified as A, B, C, or D per descriptions in Table A-1.

- *Curve Number (CN)* – 1 to 100 based on land use and soil characteristics calculated for the Discrete SCS Curve Number Method (Table A-2). If contributing watershed is composed of multiple land uses, a composite CN can be calculated by taking the weighted average CN, based on land use area.
- *Rational Runoff Coefficient (C)* – Based on land use determined for Rational Method (Table A-3). If contributing watershed is composed of multiple land uses, a composite C can be calculated by taking the weighted average C, based on land use area.

Table A-1 Four hydrologic soil groups, defined. (from NC DENR Stormwater BMP Manual)

Group A	A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr). The textures of these soils are typically sand, loamy sand, or sandy loam.
Group B	B soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15-0.30 in/hr). The textures of these soils are typically silt loam or loam.
Group C	C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05-0.15 in/hr). The texture of these soils is typically sandy clay loam.
Group D	D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr). The textures of these soils are typically clay loam, silty clay loam, sandy clay, silty clay, or clay.

Table A-2 Runoff curve numbers (CN) in urban areas from NC DENR Stormwater BMP Manual

Cover Description	Curve Numbers for Hydrologic Soil Group			
	A	B	C	D
<i>Fully developed urban areas</i>				
Open Space (lawns, parks, golf courses, etc.)				
Poor condition (< 50% grass cover)	68	79	86	89
Fair condition (50% to 75% grass cover)	49	69	79	84
Good condition (> 75% grass cover)	39	61	74	80
Impervious areas:				
Paved parking lots, roofs, driveways, etc.	98	98	98	98
Streets and roads:				
Paved; curbs and storm sewers	98	98	98	98
Paved; open ditches	83	89	98	98
Gravel	76	85	89	91
Dirt	72	82	85	88
 <i>Developing urban areas</i>				
Newly graded areas	77	86	91	94
Pasture (< 50% ground cover or heavily grazed)	68	79	86	89
Pasture (50% to 75% ground cover or not heavily grazed)	49	69	79	84
Pasture (>75% ground cover or lightly grazed)	39	61	74	80
Meadow - continuous grass, protected from grazing and generally mowed for hay	30	58	71	78
Brush (< 50% ground cover)	48	67	77	83
Brush (50% to 75% ground cover)	35	56	70	77
Brush (>75% ground cover)	30	48	65	73
Woods (Forest litter, small trees, and brush destroyed by heavy grazing or regular burning)	45	66	77	83
Woods (Woods are grazed but not burned, and some forest litter covers the soil)	36	60	73	79
Woods (Woods are protected from grazing, and litter and brush adequately cover the soil)	30	55	70	77

Table A-3 Rational runoff coefficients from NC DENR Stormwater BMP Manual

Description of Surface	Rational Runoff Coefficients, C
Unimproved Areas	0.35
Asphalt	0.95
Concrete	0.95
Brick	0.85
Roofs, inclined	1.00
Roofs, flat	0.90
Lawns, sandy soil, flat (<2%)	0.10
Lawns, sandy soil, average (2-7%)	0.15
Lawns, sandy soil, steep (>7%)	0.20
Lawns, heavy soil, flat (<2%)	0.15
Lawns, heavy soil, average (2-5%)	0.20
Lawns, heavy soil, steep (>7%)	0.30
Wooded areas	0.15

Precipitation Characteristics

- *Design Precipitation Depth (P)* – Based on location and ARI, inches
- *Design Precipitation Intensity (I)* – Based on location and ARI, inches per hour
- *Time of Concentration (Tc)* – Calculated for the contributing watershed using any regulation approved method. Some examples of these include
 - *US Federal Aviation Administration equation*

$$t = 1.8 (1.1 - C) L^{0.5} / (100 S)^{1/3}$$

- *Kirpich equation*

$$t = 0.0078 k (L / S^{0.5})^{0.77}$$

- *Kerby equation*

$$t = 0.8268 (L r / S^{0.5})^{0.467}$$

where C = is the runoff coefficient from the Rational Method (as determined in “Watershed Characteristics”

L = longest watercourse length (ft)

S = average slope of watercourse, ft/ft

t = time of concentration, min

k = Kirpich adjustment factor (Table A-4)

r = Kerby retardance roughness coefficient (Table A-5)

Table A-4 Kirpich adjustment factors for different ground covers

Ground Cover	Kirpich Adjustment Factor, k (Chow et al., 1988; Chin, 2000)
General overland flow and natural grass channels	2.0
Overland flow on bare soil or roadside ditches	1.0
Overland flow on concrete or asphalt surfaces	0.4
Flow in concrete channels	0.2

Table A-5 Kerby retardance roughness coefficients for different ground covers

Ground Cover	Kerby Retardance Coefficient, r (Chin, 2000)
Conifer timberland, dense grass	0.80
Deciduous timberland	0.60
Average grass	0.40
Poor grass, bare sod	0.30
Smooth bare packed soil, free of stones	0.10
Smooth pavements	0.02

ii. Outputs

- S – potential maximum retention after rainfall begins, in inches, calculated by

$$S = 1000/CN - 10$$

- Q – Runoff volume from the contributing watershed, in inches, calculated by

$$Q = (P - 0.2S)^2 / (P + 0.8S)$$

where P is rainfall depth (in)

- *Runoff Volume* – Runoff volume from the contributing watershed converted from inches to cubic feet

- *Peak Flow* – Maximum design discharge for the storm event, in cfs, calculated by

$$Q = C \cdot I \cdot A$$

where C is the composite rational runoff coefficient for the watershed, calculated above

I is rainfall intensity (in/hr) for the design storm



A is the area of the watershed (ac)

b. "RSC Design" Tab (orange)

	A	B	C	D	E	F	G	H	I
1									
2	Pool Design Characteristics								
3									
4				Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	
5		Length of Pool (lp), ft =		30	20	20	20	20	
6		Width of Pool (wp), ft =		15	15	15	15	15	
7		Depth of Pool (dp), ft =		1.5	1.5	1.5	1.5	1.5	
8									
9		Depth of Cobble Layer (dc), ft =		1.5	1.5	1.5	1.5	1.5	
10		Depth of Sand Media Layer (dm), ft =		2	2	2	2	2	
11									
12		Width of Meida Bed Base (bw), ft =		8	8	8	8	8	
13		Width of Cobble Base (cbw), ft =		12	12	12	12	12	
14		Width of Pool Bed (pbw), ft =		9	9	9	9	9	
15									
16		Length of Media Bed Base (bl), ft =		30	20	20	20	20	
17		Length of Cobble Bed Base (cbl), ft =		21	11	11	11	11	
18		Length of Pool Base (pbl), ft =		21	11	11	11	11	
19									
20		Total Depth, ft =		5	5	5	5	5	
21									
22	Riffle Design Characteristics								
23									
24				Riffle 1	Riffle 2	Riffle 3	Riffle 4	Riffle 5	
25		Length of Riffle (rl), ft =		8	8	8	8	8	
26		Wdith of Riffle (rw), ft =		15	15	15	15	15	
27		Depth of Riffle (rd), ft =		1	1	1	1	1	
28		Total Elev Drop over Riffle (rh), ft =		0.5	0.5	0.5	0.5	0.5	
29									
30		Riffle Slope =		16	16	16	16	16	
31				6%	6%	6%	6%	6%	
32		Parabolic Riffle Coefficient (a) =		14.0625	14.0625	14.0625	14.0625	14.0625	
33									
34	Planting Characteristics								
35									
36					K				
37		Species Water Requirements	Mod		0.5				
38		Planting Density	High		1.2				
39		Microclimate	High		1.25				
40			KL		0.75				
41									

* Microclimate - increased (high) or decreased (low) ET conditions from open field (mod), i.e. sunny/pavement = high

Figure A-3 Screen shot of RSC design parameters on orange "RSC Design" tab

Selection of the orange tab labeled “RSC Design” should result in the left side of the screen as shown in Figure A-3, with varying values in the cells. Blue  cells are model user inputs. Red  cells are determined based on the inputs and may be useful to know. The model user should not adjust red cells.

i. Inputs

The RSC design for this model allows for five consecutive cells (pool/riffles). Fixed design parameters include side slopes of pools and media bed, as depicted in Figure A-4. Input dimensions for each component, in feet, are described below

Pool Design Characteristics

- *Length (lp)*
- *Width (wp)*
- *Depth (dp)*
- *Depth of Cobble Layer (dc)*
- *Depth of Sand Media Layer (dm)*

Riffle Design Characteristics

- *Length (lr)*
- *Width (wr)*
- *Depth (dr)*
- *Drop (hr)*

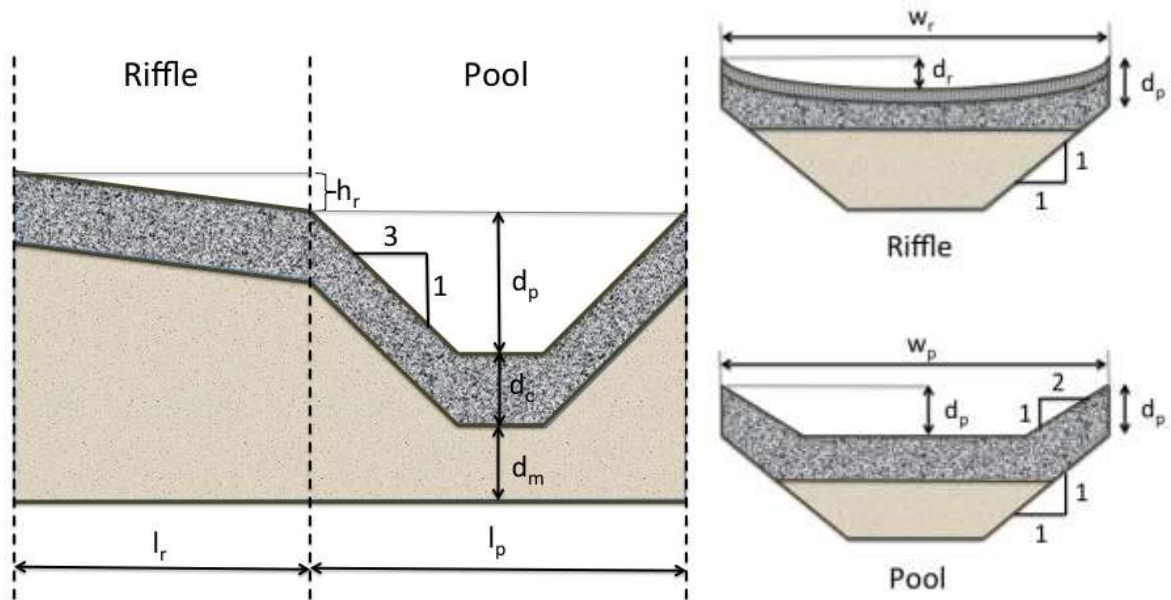


Figure A-4 RSC cell and associated dimensions

Planting Characteristics

Planting characteristics are important for determining evapotranspiration within the RSC. Evapotranspiration, in this model, is calculated using the ET_c formula, described as

$$ET_c = (K_c)(ET_o)$$

where ET_c is the evapotranspiration attributed to that specific crop
 K_c is the crop coefficient associated with the specific crop
 ET_o is a reference evapotranspiration value given for the location

When groundcover is not planted as a monocrop, this equation can still be used by replacing K_c with a landscape coefficient (K_L) (Costello et al., 2000), described by

$$K_L = (K_s)(K_d)(K_{mc})$$

This model requires inputs for K_s , K_d , and K_{mc} as described below

- *Vegetation water requirements (K_s)* – dependent on the plant species and region planted, a good rule of thumb is using species irrigation requirements (Costello and Jones, 1999), such that
 - Low = irrigation requirements are < 30% that of ET_o
 - Moderate = irrigation requirements are 40% to 60% that of ET_o
 - High = irrigation requirements are 70% to 90% that of ET_o
- *Planting diversity (K_d)* – Defined by
 - Low = Immature, sparse cover
 - Moderate = full cover, but primarily one species
 - High = mixed species, trees, shrubs, and groundcovers
- *Microclimate (K_{mc})* – Defined by
 - Low = Shaded, protected from winds
 - Moderate = Similar to open-field setting
 - High = Around features which increase ET rates, such as median or parking lots
- Output values associated with each category (Low, Mod, High) are determined based on Costello et al. (2000).

c. Model Output

The model output, based on input parameters, is located on the right-hand side of the “RSC Design” tab (Figure A-5).

- *Hydrographs* – The modeled inflow and cell outflow surface hydrographs are plotted using the Malcom Method (see Model Calculations below). This is a

commonly used metric of SCM hydrologic performance, and illustrates both peak flow and runoff volume reductions.

- *Runoff Fate* – A pie chart associated with each cell shows the end fate of the runoff. Runoff can leave the RSC as surface flow, subsurface seepage, evapotranspiration, or exfiltration into parent soils.

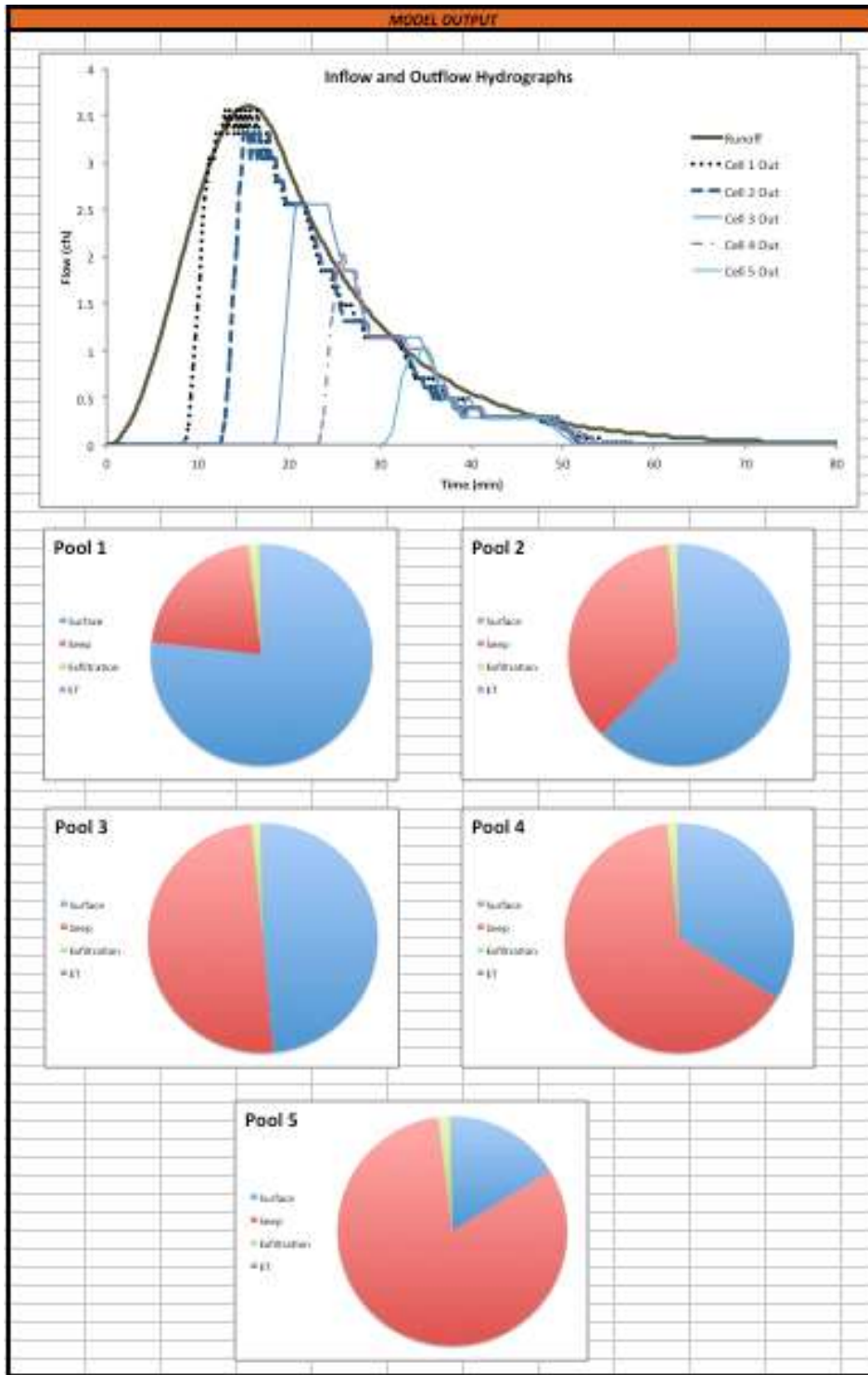


Figure A-5 Screen shot of "Model Output" section on "RSC Design" tab

Model Calculations

a. Stage-Storage Tables

Stage-storage tables for the RSC cell (black tab, Cell # S-S), including the pore space within the media were created for each RSC cell within the design (up to 5 cells in series). These tables were based on RSC cell geometry provided in the inputs and standard side slopes. Porosities for the cobble and sand media were set as 0.25 and 0.3, respectively, based on Figure 6.

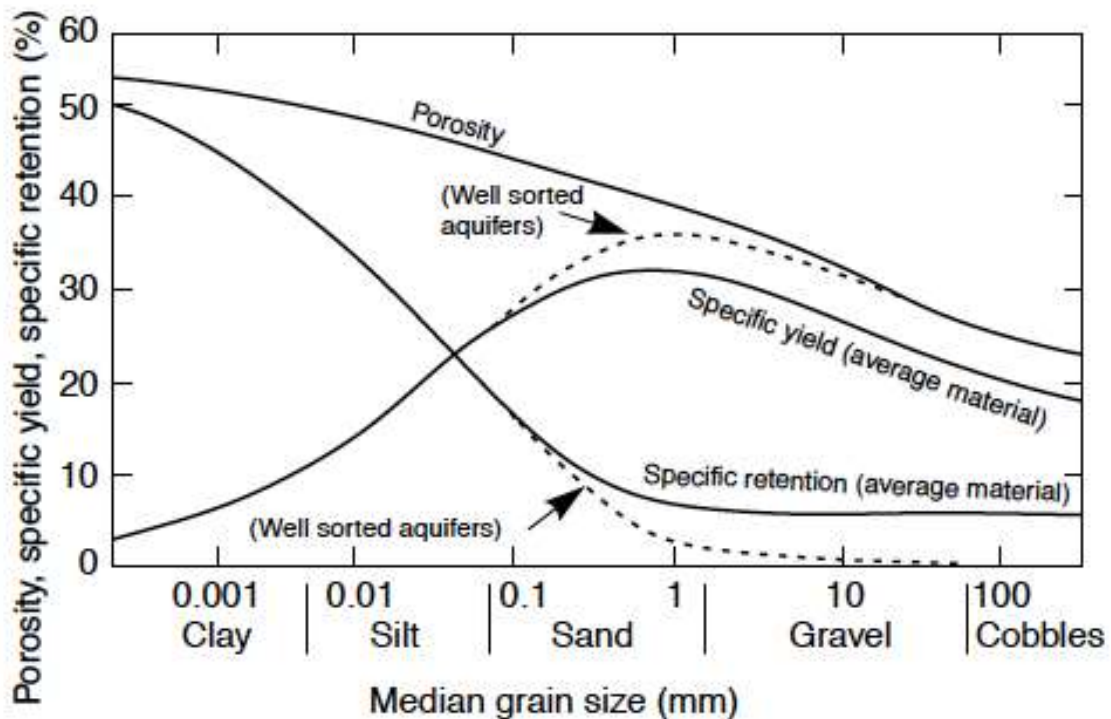


Figure A-6 Porosity of media based on grain size (from Stephens et al., 1998)

Stage-storage tables were also created for the open pool space (black tab, Cell # Surf S-S) to aid in surface accumulation (prior to infiltration), based, again, on pool geometry provided by inputs.

b. Hydrographs

A runoff inflow hydrograph is estimated using Malcom's Method as described by Malcom (1995), given the design storm characteristic put into the model. Surface outflow from each pool is calculated using an empirical model for flow over parabolic weirs, as described by Sommerfeld and Stallybrass (1996), as follows

$$Q = C_0 \frac{\pi h^2 \sqrt{2ag}}{2}$$

where, C_0 is a discharge coefficient to account for friction loss over the weir, 0.6 for circular weirs and used in these calculations as well

h is the driving head over the center of the weir

g is the acceleration due to gravity (32.2 ft/s)

a is a measure of flatness of the parabola, such that

$$x^2 = 4ay$$

For the RSC cell described, a is calculated as follows

$$a = \frac{w_r^2}{16d_r}$$

Using the above equations, flow rates are calculated at time increments of 0.25 minutes for the first 120 minutes, and then 10 minutes for the remaining time interval.

c. Water Balance

Once runoff enters the system, it can leave as surface flow, subsurface seepage, evapotranspiration, and exfiltration into the parent soil.

i. Surface flow

Surface flows were calculated at 0.25-min increments for the first 120 min, and then at 10-min intervals for the remaining time span by balancing the *in*'s and *out*'s, such that

$$S_{\text{pool},t} = S_{\text{pool},t-\Delta t} + Q_{\text{in},t} \Delta t - Q_{\text{out}} \Delta t - \text{Infil}$$

where, $S_{\text{pool},t}$ is the water stored in the pool at time t or $t - \Delta t$
 Δt is equal to the time increment between the current time and the previous time
 $Q_{\text{in},t}$ is the inflow at time t
 $Q_{\text{out},t}$ is the outflow from the pool at time t
Infil is the water infiltrated into the RSC media

The infiltration rate into the sand media is a function of the stage in the pool, and is described by a regression model of well data at an RSC in Alamance County (Figure A-7), such that

$$K_{\text{sand}} = 0.167 \cdot h - 0.2093 \text{ [=] ft/hr}$$

where, k is the instantaneous infiltration rate at stage h

From the infiltration rate, we can calculate the volume infiltrated during time interval t as

$$\text{infil} = (K_{\text{sand}})(SA) \Delta t$$

It is important to note that the model will not allow infiltration beyond what is in storage. Therefore, if there is a volume stored in the pool at time t that is less than what is calculated to be infiltrated, the model will only allow what is stored to be infiltrated. The inflow to the cell is either from the Malcom inflow hydrograph or the outflow from the preceding cell.

ii. Exfiltration

Once the media is filled, RSCs are expected to promote exfiltration into parent soils, hence reducing overall runoff volumes. A lag is expected between when water begins infiltrating into the media and when the water has contact with the bottom of the system. This lag is estimated as depth of the media bed divided by the infiltration rate at the interface of the media. Once the water reaches the bottom of the cell, exfiltration is estimated to occur at a constant rate determined by the parent soil based on the HSG.

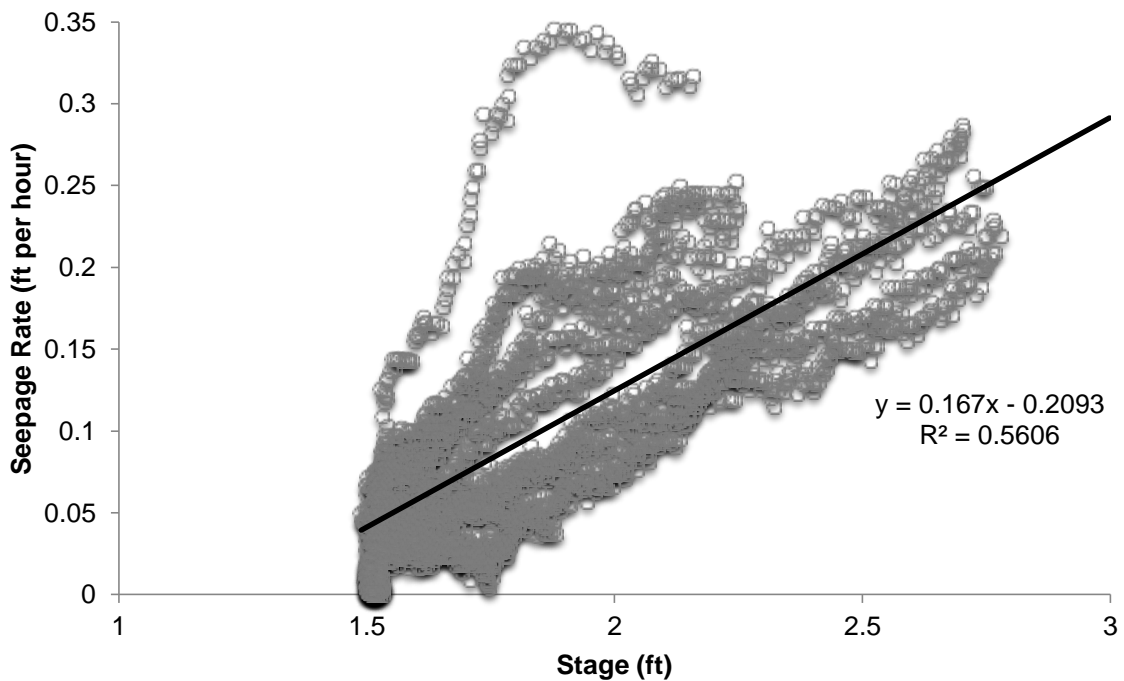


Figure A-7 Regression analysis of summer 2013 well data within sand media at Alamance RSC

iii. Evapotranspiration

Evapotranspiration (ET) is estimated using the Penman Monteith reference ET values (ET_0). Average daily reference values were calculated for a station in each of

NC's eco-regions (Coastal Plain – Wilmington, Piedmont – Raleigh, Mountains – Boone) using monthly measured data from February 2010. The landscape coefficient is calculated based on the amount of water the plant species chosen use, density and diversity of plantings, and the surrounding microclimate (described in inputs). The final landscape coefficient (K_L) is calculated as

$$K_L = K_s K_d K_{mc}$$

Therefore, the ET for each time interval is

$$ET_t = K_L ET_0 SA$$

where SA is the surface area of the cell

iv. Seepage

Once water enters the media, it is expected to preferentially flow along the cobble/sand interface. The sand has a smaller infiltration rate, so the same media infiltration rate as that for infiltration into the sand media bed is not used for seepage. Instead the infiltration rate (K_{cob}) is calculated from regression analysis of well data water levels in the cobble layer from the Alamance RSC (Figure A-7), such that

$$K_{cob} = 15.387h - 31.124 [=] \text{ ft/hr}$$

Darcy's Law is then used to calculate the horizontal seepage flux as follows

$$q_{seep} = K \frac{dh}{dL} = K_{cob} \frac{h_r}{l_r + l_p}$$

It is assumed that the media interface generally follows the slope of the surface, and therefore, the overall dh is estimated by the drop between the inlet of a cell and the

outlet of the cell. The flux of seepage is through the vertical cross-section, which is calculated using by the geometry of the cell at the riffle times the porosity of the media. As with the infiltration and exfiltration calculations, seepage will not occur unless the appropriate storage is available. Additionally, seepage may enter the system if the cell is not the first cell in the series.

v. Overall Water Balance

An overall water balance for each cell, and subsequently a series of cells using the following water balance

$$\text{Surface IN} = \text{Surface OUT} + \text{Exfiltration} + \text{ET} + \text{Seepage}$$

Using the above water balance, system performance can be hydrologically evaluated.

d. Model Assumptions

There are many assumptions made in the design of this model. Important assumptions include

- Media bed is longitudinally smooth, with a constant slope for the duration of RSC length
- Precipitation into each cell is negligible
- Once water enters media, flux is primarily downward at a constant rate until the next media interface (i.e. cobble/sand interface and sand/parent soil interface)
- Media drains completely between storm events

Example Model Validation

The model output is compared to an actual storm event on July 14, 2013 at the Alamance County RSC. Based on the model assumptions, only the first three cells were assessed (Figure A-8, Figure A-9). The fourth cell at the site is designed to

store water in its subsurface, which was not considered in the model. Model inputs and outputs are compared to the actual system performance (Table A-6).

The model does not simulate actual flow through this RSC system particularly well, although there are several good signs. The model shows the predominant flow through the system as surface flow, where the monitored site shows predominantly seepage. This may be a result of the monitoring equipment – a compound v-notch/broad crested weir, which allows much less surface flow through than the full width boulder parabolic weir. With less water leaving each cell as surface, there is more ponding and, therefore, more infiltration. It will be necessary to monitor RSCs at the inlet and outlet, without internal monitoring weirs to confirm this theory. The accuracy of the models predictions at this site may reveal a more validated model. Additionally, the model appears to predict ET and exfiltration well. ET is such a small piece of the water budget that this milestone may not be overly significant for performance predictions. The close representation of exfiltration is encouraging, as this is a predominant way of reducing outflow volume, and therefore, of high interest to engineers and regulators. Future adjustments and calibration of the model will with no doubt produce more accurate results.

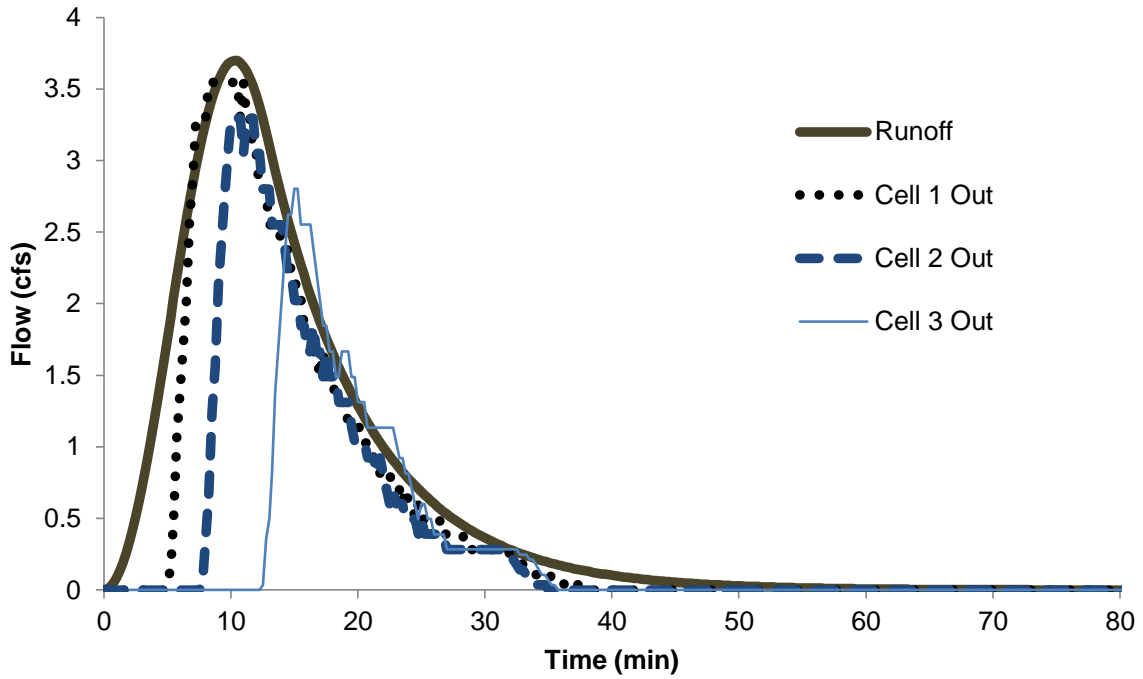


Figure A-8 Hydrograph output from modeled July 14 storm event at Alamance RSC

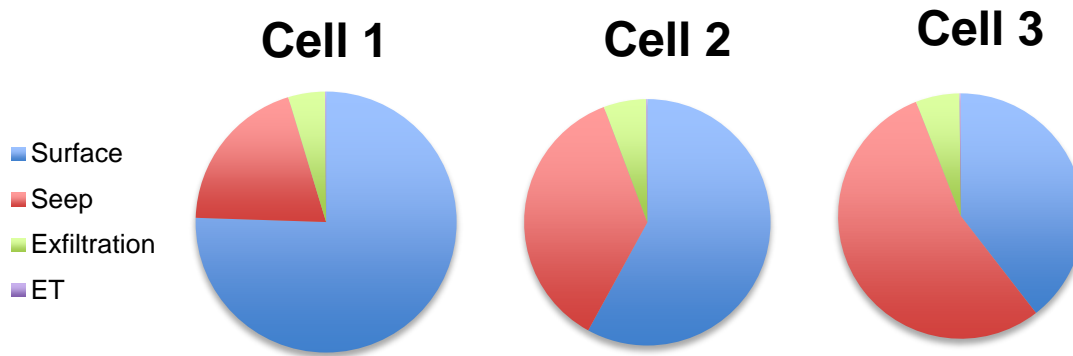


Figure A-9 Runoff fate from each cell in series

Table A-6 Model inputs and outputs for July 14, 2013 storm at Alamance RSC

<i>Model Inputs</i>			
Runoff Volume =	3178	cf	
Peak Flow =	3.67	cfs	
	Pool 1	Pool 2	Pool 3
Length of Pool (lp), ft =	19	20.5	21.75
Width of Pool (wp), ft =	15	15	15
Depth of Pool (dp), ft =	1.5	1.5	1.5
	1.5	1.5	1.5
Depth of Cobble Layer (dc), ft =	1.5	1.5	1.5
Depth of Sand Media Layer (dm), ft =	3	3	3
	Riffle 1	Riffle 2	Riffle 3
Length of Riffle (lr), ft =	8	8	8
Width of Riffle (wr), ft =	15	15	15
Depth of Riffle (dr), ft =	1	1	1
Total Elev Drop over Riffle (hr), ft =	0.5	0.25	0.5
<i>Water Balance</i>			
		Monitored	Modeled
<i>Pool 1</i>			
Surface	<i>In</i>	3189	3189
	<i>Out</i>	857	2527
Seepage	<i>In</i>	0	0
	<i>Out</i>	2191	622
Exfiltration	<i>Out</i>	140	152
ET	<i>Out</i>	1	4
<i>Pool 2</i>			
Surface	<i>In</i>	857	2527
	<i>Out</i>	761	1918
Seepage	<i>In</i>	2191	662
	<i>Out</i>	2172	1201
Exfiltration	<i>Out</i>	133	184
ET	<i>Out</i>	1	5
<i>Pool 3</i>			
Surface	<i>In</i>	761	1918
	<i>Out</i>	186	1310
Seepage	<i>In</i>	2172	1201
	<i>Out</i>	2616	1810
Exfiltration	<i>Out</i>	149	192
ET	<i>Out</i>	1	6

Model Implications for RSC Design and Performance

A RSC was designed for a standard one-acre watershed ($C = 0.65$, $CN = 78$, HSG C), and its performance was compared for different design scenarios – $P = 0.25$ inch, $P = 1$ inch, and $P = 2$ in (Table A-7). As expected, there was very little surface flow exiting the first pool during the smallest storm, and the proportion of surface flow gradually increased as the storm size increased. There was not any surface flow exiting the RSC system for either the 0.25-in and 1-in storm events, indicating that the system can very adequately mitigate the water quality event for the Piedmont.

Table A-7 Model outputs for RSC designed for 1-acre watershed during different storm events

	Cell 1					
	P = 0.25 inch		P = 1.0 inch		P = 2.0 inch	
	In	Out	In	Out	In	Out
Surface	143	47	213	109	1758	1527
Seepage		93		100		229
Exfiltration		41		42		95
ET		4		4		4
Total System (3 Cells)						
Surface	143	0	213	0	1758	1166
Seepage		136		203		596
Exfiltration		72		98		228
ET		15		15		15

RSC design parameters were adjusted on the same hypothetical RSC in the same hypothetical watershed under a 1-inch storm event (Table A-8). When the depth of the pool was decreased, but the pool dimensions were adjusted such the storage volume was not affected, very little change in surface flow occurs. However, if the pool depth is increased and other dimensions maintained (not shown), then the ponding volume increases, decreasing surface flow and increasing seepage and exfiltration. Increasing media depth in bioretention cells have been shown to

increase exfiltration by holding water within the system in contact with parent soil for a longer period of time. When the media depth is increased in an RSC, exfiltration does not appear to increase, and may decrease. However, seepage appears to increase with media depth. This makes more sense for an RSC, as these are conveyance systems, intending to move water. Moreover, seepage is managed, treated, slow release stormwater. When the slope of the riffle decrease, the hydraulic seepage rate (dh/dl) will decrease. This is why we see a decrease in seepage. The model also seems to struggle with lingering seepage and associated exfiltration (beyond 5 days) when seepage rates get too low. Also, increasing the number of cells in a series decreases surface flow and increases the other pathways.

Table A-8 RSC design changes and associated fate of runoff

	In	Cell 1 - Out					
		Pool Depth		Media Depth		Riffle Slope	
		$d_p = 1.5$ ft, $V_p = 79$ cf	$d_p = 1$ ft, $V_p = 80$ cf	$d_m = 2$	$d_m = 2.5$	13% Slope	3% Slope
Surface	213	109	107	109	107	109	109
Seepage		100	105	100	105	100	97
Exfiltration		42	39	42	39	42	42
ET		4	4	4	4	4	4
	In	Total System (3 Cells) - Out					
Surface	213	0	0	0	0	0	0
Seepage		203	196	203	70+	203	96+
Exfiltration		98	93	98	97+	98	88+
ET		15	19	15	15	15	10

Conclusions

The “RSC Working Model” has room for much improvement as more data becomes available on RSC performance, but it already is a useful tool in estimating how

system design factors may affect overall cell and system performance. General design recommendations include increasing pool volume and depth, increasing and media depth. Unfortunately, each of these recommendations is associated with an increase in cost. These design considerations must be balanced. In each of the simulations, three cells appeared adequate to manage the water quality event with greatly reduced surface flows. More work is needed in incorporating data for better quantifying seepage rates and subsurface flow (regressions are low). The model also needs validating from a variety of different RSC sites.

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B. Hydrologic Data from Alamance County RSC

Table B-1 Water balance summary for inflow producing storms during monitoring period

Ss ¹	Date	Rain	In	Cell 1					Cell 2					Cell 3					Cell 4				
			m ³	Srf	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET
1	7/10/13	28	218	10	8	220	0	0	3	39	192	0	0	3	24	210	0	0	9	61	171	1	10
1	7/14/13	12	90	4	78	15	0	0	1	13	82	0	0	1	8	88	0	0	8	17	71	1	10
1	7/21/13	4	9	1	0	10	0	0	0	0	11	0	0	0	0	11	0	0	1	0	0	0	11
1	7/25/13	15	139	5	116	28	0	0	1	50	95	0	0	2	24	123	0	0	5	41	115	0	1
1	7/27/13	17	127	6	129	15	0	0	2	50	106	0	0	2	24	146	0	0	6	45	138	0	5
1	7/28/13	5	52	1	36	16	0	0	0	13	40	0	0	0	5	48	0	0	1	21	35	0	2
1	8/6/13	14	173	5	65	114	0	0	1	32	148	0	0	2	18	163	0	0	5	33	146	1	10
1	8/17/13	16	43	6	30	19	0	1	1	7	43	0	1	2	10	40	0	1	5	33	21	0	1
1	8/19/13	6	129	2	90	40	0	0	1	74	57	0	1	1	35	95	0	1	2	29	97	0	6
1	9/1/13	81	657	29	537	149	0	0	8	181	513	0	0	10	175	529	0	0	26	234	507	0	6
2	9/20/13	6	59	2	41	20	0	0	1	4	58	0	0	1	5	57	0	0	2	0	61	0	3
2	9/21/13	13	35	5	36	3	0	0	1	26	14	0	0	2	17	25	0	0	4	24	15	6	0
2	10/7/13	13	144	5	91	58	0	0	1	19	131	0	0	2	20	131	0	0	4	19	155	0	7
2	10/10/13	13	142	5	123	24	0	0	1	53	95	0	0	2	31	119	0	0	4	40	110	0	4
2	11/1/13	10	115	3	96	23	0	0	1	17	102	0	0	1	16	104	0	0	3	19	117	0	6
2	11/12/13	3	27	1	0	28	0	0	0	0	28	0	0	0	0	28	0	0	1	0	28	0	1
2	11/15/13	3	13	1	10	4	0	0	0	0	14	0	0	0	0	15	0	0	1	0	17	0	1
2	11/17/13	4	14	1	13	2	0	0	0	1	14	0	0	0	0	15	0	0	1	0	29	0	6
2	11/26/13	42	587	15	436	166	0	1	4	66	539	0	1	5	41	569	0	1	14	70	567	1	7

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

Table B-1 (continued)

Ss ¹	Date	Rain	In	Cell 1					Cell 2					Cell 3					Cell 4				
			m ³	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET	Ex	RO	Srf Out	Seep	ET	Ex
3	12/7/13	9	89	3	73	18	0	0	1	29	63	0	0	1	13	80	0	0	3	6	84	0	5
3	12/9/13	6	45	2	44	3	0	0	1	3	44	0	0	1	1	47	0	0	2	1	46	0	3
3	12/14/13	17	89	3	73	18	0	0	1	29	63	0	0	1	13	80	0	0	3	6	84	0	5
3	12/22/13	34	502	12	333	180	0	1	3	103	413	0	1	4	41	478	0	1	11	25	495	0	10
3	1/10/14	42	582	30	508	103	0	1	8	436	182	0	1	10	230	398	0	1	27	313	333	1	8
3	1/14/14	9	77	6	48	35	0	0	2	27	57	0	0	2	12	74	0	0	6	24	60	0	8
3	2/4/14	10	96	3	81	19	0	0	1	31	68	0	0	1	12	89	0	1	3	20	80	0	3
3	2/12/14	24	326	9	66	268	0	1	2	56	280	0	1	3	25	313	0	1	8	10	330	0	5
3	2/21/14	14	158	5	142	20	0	0	1	68	95	0	0	2	28	137	0	0	5	40	118	0	10
3	3/3/14	12	121	4	93	33	0	0	1	26	99	0	0	1	10	117	0	0	4	9	114	0	7
3	3/6/14	62	910	22	754	178	0	0	6	401	537	0	0	8	170	775	0	0	20	275	686	0	4
4	3/16/14	13	131	5	52	84	0	0	1	13	123	0	0	2	3	135	0	0	4	4	129	0	8
4	3/17/14	26	366	9	113	262	0	0	2	52	325	0	0	3	16	364	0	0	8	22	359	0	8
4	3/18/14	6	44	2	4	42	0	0	1	0	47	0	0	1	0	48	0	0	2	0	50	0	0
4	3/23/14	5	24	2	16	9	0	0	0	5	20	0	0	1	1	25	0	0	1	0	21	0	5
4	3/28/14	7	47	2	28	21	0	1	1	5	44	0	1	1	0	49	0	1	2	0	40	1	10
4	4/7/14	40	554	14	412	156	0	1	4	303	268	0	0	5	127	336	0	1	13	127	341	0	8
4	4/15/14	26	341	10	195	155	0	1	3	136	215	0	0	3	56	298	0	0	9	56	299	0	8
4	4/18/14	13	153	5	101	56	0	1	1	18	139	0	0	2	4	155	0	0	4	6	148	0	8
4	5/10/14	7	54	3	41	14	0	1	1	23	33	0	0	1	7	49	0	0	2	4	46	0	8
4	5/15/14	54	777	19	488	307	0	1	5	378	422	0	0	7	156	650	0	0	17	170	646	0	8
4	5/27/14	20	144	7	15	136	0	0	2	4	149	0	0	2	0	155	0	0	6	0	158	0	4
1	6/10/14	20	240	7	156	90	0	0	2	53	196	0	0	2	18	233	0	0	6	49	201	0	7

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

C. Appendix: Water Quality Data for Alamance County RSC

Table C-1 Data for each water quality event at the Inlet location

Ss ¹	Flow m ³	TN mg L ⁻¹	TKN mg L ⁻¹	NOx mg L ⁻¹	NH ₃ mg L ⁻¹	TP mg L ⁻¹	OP mg L ⁻¹	TSS mg L ⁻¹
1	218	2.15	1.94	0.21	0.11	0.33	0.22	25.71
1	90	1.59	1.39	0.20	0.14	0.31	0.10	42.33
1	752	1.84	1.63	0.21	0.32	0.36	0.23	8.82
1	657	2.40	2.17	0.23	0.31	0.64	0.49	69.14
2	59	2.93	2.55	0.37	0.88	0.36	0.25	26.25
2	144	6.79	5.86	0.93	2.66	2.14	1.65	71.16
2	142	1.85	1.55	0.29	0.36	0.44	0.29	74.87
2	115	3.95	3.08	0.87	0.75	0.66	0.50	86.79
2	587	5.45	4.89	0.56	1.94	0.76	0.53	44.22
3	582	1.84	1.61	0.23	0.13	0.58	0.29	97.43
3	77	1.68	1.45	0.23	0.31	0.28	0.15	41.22
3	158	4.28	4.07	0.21	0.35	0.71	0.13	296.60
3	121	9.96	9.31	0.65	1.75	0.88	0.62	90.08
3	910	2.68	2.35	0.33	0.77	0.39	0.20	52.58
4	47	5.44	5.16	0.27	1.45	0.55	0.19	81.46
4	554	1.63	1.41	0.23	0.27	0.37	0.13	72.50
4	341	4.47	4.30	0.18	0.39	0.61	0.22	103.08
4	153	ND	ND	ND	ND	ND	ND	ND
4	777	1.80	1.56	0.24	0.15	0.34	0.18	37.81
1	240	1.73	1.37	0.36	0.20	0.24	0.11	39.52

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

ND = no data

Table C-2 Data for each water quality event at the Outlet 1 location

Ss ¹	Flow m ³	TN mg L ⁻¹	TKN mg L ⁻¹	NOx mg L ⁻¹	NH ₃ mg L ⁻¹	TP mg L ⁻¹	OP mg L ⁻¹	TSS mg L ⁻¹
1	8	2.03	1.79	0.25	0.11	0.41	0.30	10.51
1	78	3.24	2.63	0.61	0.89	0.47	0.28	20.22
1	320	1.58	1.36	0.23	0.21	0.43	0.34	10.36
1	537	3.27	2.97	0.30	0.38	0.54	0.35	11.28
2	41	1.38	1.13	0.25	0.31	0.24	0.17	14.18
2	91	0.84	0.35	0.49	1.81	1.52	1.28	68.06
2	123	1.89	1.50	0.39	0.34	0.53	0.39	59.11
2	96	5.64	5.41	0.23	1.41	0.86	0.68	46.95
2	436	3.59	3.04	0.54	1.00	0.55	0.43	19.04
3	508	2.58	2.17	0.41	0.55	0.44	0.16	75.42
3	48	1.64	1.39	0.25	0.34	0.28	0.17	23.73
3	142	4.26	4.03	0.23	0.33	0.75	0.14	261.10
3	93	8.10	7.49	0.61	1.85	0.80	0.59	64.59
3	754	2.68	2.40	0.28	0.67	0.42	0.23	60.65
4	28	2.28	2.03	0.25	0.77	0.30	0.13	29.64
4	412	2.14	1.90	0.24	0.32	0.35	0.17	55.56
4	195	3.34	3.19	0.15	0.35	0.53	0.21	76.99
4	101	1.89	1.71	0.18	0.21	0.23	0.13	18.54
4	488	1.55	1.36	0.19	0.15	0.31	0.18	28.30
1	156	1.76	1.33	0.43	0.15	0.27	0.13	29.21

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

ND = no data

Table C-3 Data for each water quality event at the Outlet 2 location

Ss ¹	Flow m ³	TN mg L ⁻¹	TKN mg L ⁻¹	NOx mg L ⁻¹	NH ₃ mg L ⁻¹	TP mg L ⁻¹	OP mg L ⁻¹	TSS mg L ⁻¹
1	39	1.74	1.55	0.18	0.10	0.40	0.31	6.70
1	13	1.82	1.58	0.24	0.41	0.33	0.18	21.28
1	239	1.54	1.30	0.24	0.25	0.44	0.34	7.69
1	181	1.80	1.49	0.31	0.18	0.60	0.49	9.85
2	4	0.72	0.58	0.14	0.15	0.16	0.13	10.12
2	19	3.21	2.81	0.40	1.47	1.38	1.07	91.51
2	53	1.39	1.06	0.34	0.28	0.45	0.33	54.23
2	17	1.54	1.28	0.27	0.08	0.52	0.39	33.20
2	66	1.71	1.40	0.31	0.22	0.47	0.36	30.66
3	436	1.73	1.53	0.20	0.12	0.51	0.28	83.79
3	27	1.16	0.98	0.18	0.24	0.25	0.13	25.12
3	68	4.13	3.93	0.20	0.32	0.68	0.14	209.81
3	26	5.46	4.95	0.51	1.35	0.53	0.39	72.24
3	401	2.18	1.90	0.27	0.85	0.42	0.25	51.50
4	5	2.35	2.03	0.32	0.60	0.38	0.18	76.46
4	303	1.39	1.22	0.17	0.09	0.28	0.12	48.92
4	136	1.61	1.46	0.16	0.08	0.31	0.14	41.73
4	18	1.11	0.99	0.13	0.10	0.17	0.09	13.39
4	378	1.36	1.21	0.15	0.08	0.27	0.16	34.76
1	53	1.73	1.38	0.36	0.21	0.25	0.13	51.68

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

ND = no data

Table C-4 Data for each water quality event at the Outlet 3 location

Ss ¹	Flow m ³	TN mg L ⁻¹	TKN mg L ⁻¹	NOx mg L ⁻¹	NH ₃ mg L ⁻¹	TP mg L ⁻¹	OP mg L ⁻¹	TSS mg L ⁻¹
1	24	5.64	5.16	0.47	0.39	0.61	ND	ND
1	8	6.88	6.45	0.43	3.41	0.66	0.47	ND
1	125	ND	ND	ND	ND	ND	ND	ND
1	175	1.89	1.56	0.33	0.20	0.64	0.00	10.74
2	5	1.13	0.90	0.22	0.24	0.20	0.15	13.70
2	20	3.43	2.90	0.53	1.79	1.53	1.15	48.40
2	31	1.54	1.13	0.40	0.29	0.49	0.38	29.66
2	16	1.89	1.58	0.31	0.24	0.55	0.43	21.67
2	41	1.28	1.03	0.25	0.21	0.37	0.30	22.38
3	230	2.20	1.96	0.24	0.30	0.44	0.28	75.10
3	12	1.11	0.90	0.21	0.24	0.25	0.16	13.64
3	28	4.03	3.79	0.24	0.27	0.51	0.14	84.15
3	10	5.16	4.65	0.51	1.05	0.49	0.40	32.52
3	170	1.96	1.68	0.28	0.93	0.37	0.25	19.02
4	0	ND	ND	ND	ND	ND	ND	ND
4	127	1.44	1.24	0.20	0.17	0.26	0.13	38.20
4	56	1.94	1.71	0.22	0.06	0.37	0.13	37.82
4	4	1.07	0.88	0.19	0.13	0.17	0.10	11.08
4	156	1.34	1.10	0.24	0.10	0.25	0.17	17.44
1	18	1.97	1.38	0.59	0.24	0.28	0.22	14.87

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

ND = no data

Table C-5 Data for each water quality event at the Outlet 4 location

Ss ¹	Flow m ³	TN mg L ⁻¹	TKN mg L ⁻¹	NOx mg L ⁻¹	NH ₃ mg L ⁻¹	TP mg L ⁻¹	OP mg L ⁻¹	TSS mg L ⁻¹
1	61	2.24	1.83	0.41	0.31	0.34	0.19	7.57
1	17	1.77	1.58	0.19	0.39	0.27	0.10	13.80
1	222	ND	ND	ND	ND	ND	0.26	10.14
1	234	1.76	1.46	0.29	0.20	0.54	0.43	9.98
2	0	1.68	1.43	0.24	0.25	0.18	0.08	7.70
2	19	3.85	3.07	0.78	1.35	1.23	0.99	48.19
2	40	1.41	0.95	0.46	0.25	0.41	0.28	29.37
2	19	2.08	1.56	0.52	0.14	0.45	0.33	14.31
2	70	1.44	1.13	0.31	0.13	0.39	0.31	9.73
3	313	1.20	0.99	0.22	0.12	0.37	0.26	27.26
3	24	1.05	0.86	0.19	0.17	0.20	0.13	10.21
3	40	3.19	2.97	0.23	0.24	0.41	0.13	68.50
3	9	ND	ND	ND	ND	ND	ND	ND
3	275	1.80	1.52	0.28	0.78	0.32	0.23	8.88
4	0	ND	ND	ND	ND	ND	ND	ND
4	127	1.39	1.14	0.25	0.12	0.27	0.13	22.93
4	56	2.06	1.70	0.36	0.08	0.35	0.17	21.72
4	6	1.30	0.98	0.32	0.19	0.18	0.10	8.88
4	170	1.49	1.21	0.28	0.13	0.25	0.16	12.90
1	49	1.95	1.29	0.66	0.27	0.27	0.18	9.45

¹ Ss = Season, 1 = Summer, 2 = Fall, 3 = Winter, 4 = Spring

ND = no data

D. Appendix: R-code for RSC Hydrology and Water Quality Analysis

Hydrologic Analysis

```
##### Create Subsets #####
# Subset hydro by season
h2oSum = subset(R.Hydro, Season==1)
h2oFall = subset(R.Hydro, Season==2)
h2oWin = subset(R.Hydro, Season==3)
h2oSpr = subset(R.Hydro, Season==4)

# Subset hydro by cell
h2oC1 = subset(R.Hydro, Cell==1)
h2oC2 = subset(R.Hydro, Cell==2)
h2oC3 = subset(R.Hydro, Cell==3)
h2oC4 = subset(R.Hydro, Cell==4)

# Subset WB by Cell
WB.C1 = subset(R.WB, Cell==1)
WB.C2 = subset(R.WB, Cell==2)
WB.C3 = subset(R.WB, Cell==3)
WB.C4 = subset(R.WB, Cell==4)

## Inflow and Outflow
#Wilcoxon Rank Sum Test: Volume by Cell
wilcox.test(h2oC1$Surface.IN, h2oC1$Surface.OUT, paired=TRUE)
> p < 0.0001
wilcox.test(h2oC2$Surface.IN, h2oC2$Surface.OUT, paired=TRUE)
> p < 0.0001
wilcox.test(h2oC3$Surface.IN, h2oC3$Surface.OUT, paired=TRUE)
> p < 0.0001
wilcox.test(h2oC4$Surface.IN, h2oC4$Surface.OUT, paired=TRUE)
> p = 0.0014
wilcox.test(h2oC1$Surface.IN, h2oC3$Surface.OUT, paired=TRUE)
> p < 0.0001
wilcox.test(h2oC1$Surface.IN, h2oC4$Surface.OUT, paired=TRUE)
> p < 0.0001

#Wilcoxon Rank Sum Test: Peak by Cell
wilcox.test(h2oC1$Peak.IN, h2oC1$Peak.OUT, paired=TRUE)
> p < 0.0001
wilcox.test(h2oC2$Peak.IN, h2oC2$Peak.OUT, paired=TRUE)
> p = 0.0003
wilcox.test(h2oC3$Peak.IN, h2oC3$Peak.OUT, paired=TRUE)
```

```
> p < 0.0001
wilcox.test(h2oC4$Peak.IN, h2oC4$Peak.OUT, paired=TRUE)
> p = 0.2618
wilcox.test(h2oC1$Peak.IN, h2oC3$Peak.OUT, paired=TRUE)
> p = 0.0001
wilcox.test(h2oC1$Peak.IN, h2oC4$Peak.OUT, paired=TRUE)
> p < 0.0001
```

```
#Seasonal Inflow differences
```

```
kruskal.test(Surface.IN~Season, data=h2oC1)
> p = 0.4014
kruskal.test(Surface.OUT~Season, data=h2oC1)
> p = 0.2591
kruskal.test(Surface.IN~Season, data=h2oC2)
> p = 0.2591
kruskal.test(Surface.OUT~Season, data=h2oC2)
> p = 0.1314
kruskal.test(Surface.IN~Season, data=h2oC3)
> p = 0.1314
kruskal.test(Surface.OUT~Season, data=h2oC3)
> p = 0.297
kruskal.test(Surface.IN~Season, data=h2oC4)
> p = 0.297
kruskal.test(Surface.OUT~Season, data=h2oC4)
> p = 0.0957
```

```
#Kruskal test for differences: Cell and Fate
#Seasonality in WB per cell
```

```
#Cell 1
```

```
kruskal.test(Surf.in~Season, data=WB.C1)
> p = 0.9643
kruskal.test(Surf.out~Season, data=WB.C1)
> p = 0.0361
kruskal.test(RO.in~Season, data=WB.C1)
> p = 0.9643
kruskal.test(Seep.out~Season, data=WB.C1)
> p = 0.0242
kruskal.test(ET~Season, data=WB.C1)
> p = 0.8922
kruskal.test(Exfil~Season, data=WB.C1)
> p = 0.6255
```

```
#Cell 2
```

```
kruskal.test(Surf.in~Season, data=WB.C2)
> p = 0.0361
kruskal.test(Surf.out~Season, data=WB.C2)
```

```
> p = 0.1462
kruskal.test(RO.in~Season, data=WB.C2)
> p = 0.9643
kruskal.test(Seep.in~Season, data=WB.C2)
> p = 0.0242
kruskal.test(Seep.out~Season, data=WB.C2)
> p = 0.1951
kruskal.test(ET~Season, data=WB.C2)
> p = 0.6741
kruskal.test(Exfil~Season, data=WB.C2)
> p = 0.6801
```

```
#Cell 3
```

```
kruskal.test(Surf.in~Season, data=WB.C3)
> p = 0.1462
kruskal.test(Surf.out~Season, data=WB.C3)
> p = 0.1402
kruskal.test(RO.in~Season, data=WB.C3)
> p = 0.9643
kruskal.test(Seep.in~Season, data=WB.C3)
> p = 0.1951
kruskal.test(Seep.out~Season, data=WB.C3)
> p = 0.524
kruskal.test(ET~Season, data=WB.C3)
> p = 0.8585
kruskal.test(Exfil~Season, data=WB.C3)
> p = 0.6698
```

```
#Cell 4
```

```
kruskal.test(Surf.in~Season, data=WB.C4)
> p = 0.1402
kruskal.test(Surf.out~Season, data=WB.C4)
> p = 0.0056
kruskal.test(RO.in~Season, data=WB.C4)
> p = 0.9643
kruskal.test(Seep.in~Season, data=WB.C4)
> p = 0.524
kruskal.test(Seep.out~Season, data=WB.C4)
> p = 0.0686
kruskal.test(ET~Season, data=WB.C4)
> p = 0.7626
kruskal.test(Exfil~Season, data=WB.C4)
> 0.9854
```

Water Quality Analysis

```
# Subset WQ by weir
```

```

WQ.W1 = subset(R.WQ, Weir==1)
WQ.W2 = subset(R.WQ, Weir==2)
WQ.W3 = subset(R.WQ, Weir==3)
WQ.W4 = subset(R.WQ, Weir==4)
WQ.W5 = subset(R.WQ, Weir==5)

# Subset WQ by sesason
WQ.W1.Sum = subset(WQ.W1, Season==1)
WQ.W1.Fall = subset(WQ.W1, Season==2)
WQ.W1.Win = subset(WQ.W1, Season==3)
WQ.W1.Spr = subset(WQ.W1, Season==4)

WQ.W3.Sum = subset(WQ.W3, Season==1)
WQ.W3.Fall = subset(WQ.W3, Season==2)
WQ.W3.Win = subset(WQ.W3, Season==3)
WQ.W3.Spr = subset(WQ.W3, Season==4)

WQ.W3.Sum = subset(WQ.W3, Season==1)
WQ.W3.Fall = subset(WQ.W3, Season==2)
WQ.W3.Win = subset(WQ.W3, Season==3)
WQ.W3.Spr = subset(WQ.W3, Season==4)

WQ.W4.Sum = subset(WQ.W4, Season==1)
WQ.W4.Fall = subset(WQ.W4, Season==2)
WQ.W4.Win = subset(WQ.W4, Season==3)
WQ.W4.Spr = subset(WQ.W4, Season==4)

#Shapiro-Wilk Normality Test: Weir 1
shapiro.test(WQ.W1$TN)
> p < 0.0001
shapiro.test(WQ.W1$TKN)
> p = 0.0007
shapiro.test(WQ.W1$Nox)
> p = 0.0001
shapiro.test(WQ.W1$NH3)
> p = 0.0004
shapiro.test(WQ.W1$TP)
> p < 0.0001
shapiro.test(WQ.W1$OP)
> p < 0.0001
shapiro.test(WQ.W1$TSS)
> p < 0.0001

#Shapiro-Wilk Normality Test: Weir 2
shapiro.test(WQ.W3$TN)
> p = 0.0002
shapiro.test(WQ.W3$TKN)

```

```
> p = 0.0001
shapiro.test(WQ.W3$Nox)
> p = 0.191
shapiro.test(WQ.W3$NH3)
> p < 0.0001
shapiro.test(WQ.W3$TP)
> p = 0.0002
shapiro.test(WQ.W3$OP)
> p < 0.0001
shapiro.test(WQ.W3$TSS)
> p = 0.0002
```

#Shapiro-Wilk Normality Test: Weir 3

```
shapiro.test(WQ.W3$TN)
> p = 0.0002
shapiro.test(WQ.W3$TKN)
> p = 0.0001
shapiro.test(WQ.W3$Nox)
> p = 0.191
shapiro.test(WQ.W3$NH3)
> p < 0.0001
shapiro.test(WQ.W3$TP)
> p = 0.0002
shapiro.test(WQ.W3$OP)
> p < 0.0001
shapiro.test(WQ.W3$TSS)
> p = 0.0003
```

#Shapiro-Wilk Normality Test: Weir 4

```
shapiro.test(WQ.W4$TN)
> p = 0.0009
shapiro.test(WQ.W4$TKN)
> p = 0.0006
shapiro.test(WQ.W4$Nox)
> p = 0.0125
shapiro.test(WQ.W4$NH3)
> p < 0.0001
shapiro.test(WQ.W4$TP)
> p = 0.0002
shapiro.test(WQ.W4$OP)
> p = 0.0003
shapiro.test(WQ.W4$TSS)
> p = 0.0040
```

#Shapiro-Wilk Normality Test: Weir 5

```
shapiro.test(WQ.W5$TN)
> p = 0.0050
```



```
shapiro.test(WQ.W5$TKN)
> p = 0.002
shapiro.test(WQ.W5$Nox)
> p = 0.0081
shapiro.test(WQ.W5$NH3)
> p < 0.0001
shapiro.test(WQ.W5$TP)
> p < 0.0001
shapiro.test(WQ.W5$OP)
> p < 0.0001
shapiro.test(WQ.W5$TSS)
> p < 0.0001
```

```
## Inflow and Outflow concentrations
```

```
#Wilcoxon Rank Sum Test: Weir 1 v. Weir 2
wilcox.test(WQ.W1$TKN, WQ.W2$TKN, paired=TRUE)
> p = 0.210
wilcox.test(WQ.W1$Nox, WQ.W2$Nox, paired=TRUE)
> p = 0.953
wilcox.test(WQ.W1$NH3, WQ.W2$NH3, paired=TRUE)
> p = 0.541
wilcox.test(WQ.W1$TN, WQ.W2$TN, paired=TRUE)
> p = 0.258
wilcox.test(WQ.W1$TP, WQ.W2$TP, paired=TRUE)
> p = 0.418
wilcox.test(WQ.W1$OP, WQ.W2$OP, paired=TRUE)
> p = 0.891
wilcox.test(WQ.W1$TSS, WQ.W2$TSS, paired=TRUE)
> p < 0.0001
```

```
#Wilcoxon Rank Sum Test: Weir 2 v. Weir 3
```

```
wilcox.test(WQ.W2$TKN, WQ.W3$TKN, paired=TRUE)
> p = 0.0007
wilcox.test(WQ.W2$Nox, WQ.W3$Nox, paired=TRUE)
> p = 0.0012
wilcox.test(WQ.W2$NH3, WQ.W3$NH3, paired=TRUE)
> p = 0.0005
wilcox.test(WQ.W2$TN, WQ.W3$TN, paired=TRUE)
> p = 0.0018
wilcox.test(WQ.W2$TP, WQ.W3$TP, paired=TRUE)
> p = 0.0056
wilcox.test(WQ.W2$OP, WQ.W3$OP, paired=TRUE)
> p = 0.0637
wilcox.test(WQ.W2$TSS, WQ.W3$TSS, paired=TRUE)
> p = 0.8983
```

```
#Wilcoxon Rank Sum Test: Weir 3 v. Weir 4
```

```
wilcox.test(WQ.W3$TKN, WQ.W4$TKN, paired=TRUE)
> p = 0.3927
wilcox.test(WQ.W3$Nox, WQ.W4$Nox, paired=TRUE)
> p = 0.0003
wilcox.test(WQ.W3$NH3, WQ.W4$NH3, paired=TRUE)
> p = 0.0204
wilcox.test(WQ.W3$TN, WQ.W4$TN, paired=TRUE)
> p = 0.0936
wilcox.test(WQ.W3$TP, WQ.W4$TP, paired=TRUE)
> p = 0.5226
wilcox.test(WQ.W3$OP, WQ.W4$OP, paired=TRUE)
> p = 0.0569
wilcox.test(WQ.W3$TSS, WQ.W4$TSS, paired=TRUE)
> p = 0.0002
```

```
#Wilcoxon Rank Sum Test: Weir 4 v. Weir 5
wilcox.test(WQ.W4$TKN, WQ.W5$TKN, paired=TRUE)
> p = 0.1454
wilcox.test(WQ.W4$Nox, WQ.W5$Nox, paired=TRUE)
> p = 0.1454
wilcox.test(WQ.W4$NH3, WQ.W5$NH3, paired=TRUE)
> 0.0105
wilcox.test(WQ.W4$TN, WQ.W5$TN, paired=TRUE)
> p = 0.6191
wilcox.test(WQ.W4$TP, WQ.W5$TP, paired=TRUE)
> p = 0.0007
wilcox.test(WQ.W4$OP, WQ.W5$OP, paired=TRUE)
> p = 0.0654
wilcox.test(WQ.W4$TSS, WQ.W5$TSS, paired=TRUE)
> p < 0.0001
```

```
#Wilcoxon Rank Sum Test: Weir 1 v. Weir 5
wilcox.test(WQ.W1$TKN, WQ.W5$TKN, paired=TRUE)
> p = 0.0002
wilcox.test(WQ.W1$Nox, WQ.W5$Nox, paired=TRUE)
> p = 0.8603
wilcox.test(WQ.W1$NH3, WQ.W5$NH3, paired=TRUE)
> p = 0.0290
wilcox.test(WQ.W1$TN, WQ.W5$TN, paired=TRUE)
> p = 0.0004
wilcox.test(WQ.W1$TP, WQ.W5$TP, paired=TRUE)
> p = 0.0002
wilcox.test(WQ.W1$OP, WQ.W5$OP, paired=TRUE)
> p = 0.0638
wilcox.test(WQ.W1$TSS, WQ.W5$TSS, paired=TRUE)
> p < 0.0001
```

```

#Wilcoxon Rank Sum Test: Weir 1 v. Weir 4
wilcox.test(WQ.W1$TKN, WQ.W4$TKN, paired=TRUE)
> p = 0.0569
wilcox.test(WQ.W1$Nox, WQ.W4$Nox, paired=TRUE)
> 0.7819
wilcox.test(WQ.W1$NH3, WQ.W4$NH3, paired=TRUE)
> p= 0.1454
wilcox.test(WQ.W1$TN, WQ.W4$TN, paired=TRUE)
> p = 0.0714
wilcox.test(WQ.W1$TP, WQ.W4$TP, paired=TRUE)
> p = 0.0569
wilcox.test(WQ.W1$OP, WQ.W4$OP, paired=TRUE)
> p = 0.3225
wilcox.test(WQ.W1$TSS, WQ.W4$TSS, paired=TRUE)
> p < 0.0001

## Inflow and Outflow loads
#Wilcoxon Rank Sum Test: Weir 1 v. Weir 2
wilcox.test(WQ.W1$TKN_Ld, WQ.W2$TKN_Ld, paired=TRUE)
> p = 0.0108
wilcox.test(WQ.W1$Nox_Ld, WQ.W2$Nox_Ld, paired=TRUE)
> p = 0.0095
wilcox.test(WQ.W1$NH3_Ld, WQ.W2$NH3_Ld, paired=TRUE)
> p = 0.0323
wilcox.test(WQ.W1$TN_Ld, WQ.W2$TN_Ld, paired=TRUE)
> p = 0.0082
wilcox.test(WQ.W1$TP_Ld, WQ.W2$TP_Ld, paired=TRUE)
> p = 0.0001
wilcox.test(WQ.W1$OP_Ld, WQ.W2$OP_Ld, paired=TRUE)
> p = 0.0024
wilcox.test(WQ.W1$TSS_Ld, WQ.W2$TSS_Ld, paired=TRUE)
> p < 0.0001

#Wilcoxon Rank Sum Test: Weir 2 v. Weir 3
wilcox.test(WQ.W2$TKN_Ld, WQ.W3$TKN_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W2$Nox_Ld, WQ.W3$Nox_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W2$NH3_Ld, WQ.W3$NH3_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W2$TN_Ld, WQ.W3$TN_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W2$TP_Ld, WQ.W3$TP_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W2$OP_Ld, WQ.W3$OP_Ld, paired=TRUE)
> p = 0.0005
wilcox.test(WQ.W2$TSS_Ld, WQ.W3$TSS_Ld, paired=TRUE)

```

> p < 0.0001

#Wilcoxon Rank Sum Test: Weir 3 v. Weir 4

wilcox.test(WQ.W3\$TKN_Ld, WQ.W4\$TKN_Ld, paired=TRUE)

> p = 0.0120

wilcox.test(WQ.W3\$Nox_Ld, WQ.W4\$Nox_Ld, paired=TRUE)

> p = 0.0077

wilcox.test(WQ.W3\$NH3_Ld, WQ.W4\$NH3_Ld, paired=TRUE)

> p = 0.2288

wilcox.test(WQ.W3\$TN_Ld, WQ.W4\$TN_Ld, paired=TRUE)

> p = 0.0120

wilcox.test(WQ.W3\$TP_Ld, WQ.W4\$TP_Ld, paired=TRUE)

> p = 0.0040

wilcox.test(WQ.W3\$OP_Ld, WQ.W4\$OP_Ld, paired=TRUE)

> p 0.0013

wilcox.test(WQ.W3\$TSS_Ld, WQ.W4\$TSS_Ld, paired=TRUE)

> p = 0.0002

#Wilcoxon Rank Sum Test: Weir 4 v. Weir 5

wilcox.test(WQ.W4\$TKN_Ld, WQ.W5\$TKN_Ld, paired=TRUE)

> p = 0.2633

wilcox.test(WQ.W4\$Nox_Ld, WQ.W5\$Nox_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W4\$NH3_Ld, WQ.W5\$NH3_Ld, paired=TRUE)

> p = 0.6441

wilcox.test(WQ.W4\$TN_Ld, WQ.W5\$TN_Ld, paired=TRUE)

> p = 0.0638

wilcox.test(WQ.W4\$TP_Ld, WQ.W5\$TP_Ld, paired=TRUE)

> p = 0.0232

wilcox.test(WQ.W4\$OP_Ld, WQ.W5\$OP_Ld, paired=TRUE)

> p = 0.0654

wilcox.test(WQ.W4\$TSS_Ld, WQ.W5\$TSS_Ld, paired=TRUE)

> p = 0.2524

#Wilcoxon Rank Sum Test: Weir 1 v. Weir 5

wilcox.test(WQ.W1\$TKN_Ld, WQ.W5\$TKN_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W1\$Nox_Ld, WQ.W5\$Nox_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W1\$NH3_Ld, WQ.W5\$NH3_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W1\$TN_Ld, WQ.W5\$TN_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W1\$TP_Ld, WQ.W5\$TP_Ld, paired=TRUE)

> p < 0.0001

wilcox.test(WQ.W1\$OP_Ld, WQ.W5\$OP_Ld, paired=TRUE)

> p < 0.0001

```
wilcox.test(WQ.W1$TSS_Ld, WQ.W5$TSS_Ld, paired=TRUE)
> p < 0.0001
```

```
#Wilcoxon Rank Sum Test: Weir 1 v. Weir 4
wilcox.test(WQ.W1$TKN_Ld, WQ.W4$TKN_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$Nox_Ld, WQ.W4$Nox_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$NH3_Ld, WQ.W4$NH3_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$TN_Ld, WQ.W4$TN_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$TP_Ld, WQ.W4$TP_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$OP_Ld, WQ.W4$OP_Ld, paired=TRUE)
> p < 0.0001
wilcox.test(WQ.W1$TSS_Ld, WQ.W4$TSS_Ld, paired=TRUE)
> p > 0.0001
```

```
#Kruskal-Wallis Rank Sum Test: Seasonality Effects on Pollutants
#Inflow
```

```
kruskal.test(TN~Season, data=WQ.W1)
> p = 0.2069
kruskal.test(TKN~Season, data=WQ.W1)
> p = 0.2691
kruskal.test(Nox~Season, data=WQ.W1)
> p = 0.0355
kruskal.test(NH3~Season, data=WQ.W1)
> p = 0.0473
kruskal.test(TP~Season, data=WQ.W1)
> p = 0.1725
kruskal.test(OP~Season, data=WQ.W1)
> p = 0.0643
kruskal.test(TSS~Season, data=WQ.W1)
> p = 0.0989
```

```
#Weir 1
kruskal.test(TN~Season, data=WQ.W2)
> p = 0.6066
kruskal.test(TKN~Season, data=WQ.W2)
> p = 0.5297
kruskal.test(Nox~Season, data=WQ.W2)
> p = 0.1008
kruskal.test(NH3~Season, data=WQ.W2)
> p = 0.171
kruskal.test(TP~Season, data=WQ.W2)
> p = 0.194
```

```
kruskal.test(OP~Season, data=WQ.W2)
> p = 0.0593
kruskal.test(TSS~Season, data=WQ.W2)
> p = 0.0364
```

```
#Weir 2
```

```
kruskal.test(TN~Season, data=WQ.W3)
> p = 0.2627
kruskal.test(TKN~Season, data=WQ.W3)
> p = 0.3279
kruskal.test(Nox~Season, data=WQ.W3)
> p = 0.2209
kruskal.test(NH3~Season, data=WQ.W3)
> p = 0.2006
kruskal.test(TP~Season, data=WQ.W3)
> p = 0.1866
kruskal.test(OP~Season, data=WQ.W3)
> p = 0.1176
kruskal.test(TSS~Season, data=WQ.W3)
> p = 0.0812
```

```
#Weir 3
```

```
kruskal.test(TN~Season, data=WQ.W4)
> p = 0.0928
kruskal.test(TKN~Season, data=WQ.W4)
> p = 0.2028
kruskal.test(Nox~Season, data=WQ.W4)
> p = 0.0348
kruskal.test(NH3~Season, data=WQ.W4)
> p = 0.0271
kruskal.test(TP~Season, data=WQ.W4)
> p = 0.0926
kruskal.test(OP~Season, data=WQ.W4)
> p = 0.1057
kruskal.test(TSS~Season, data=WQ.W4)
> p = 0.3167
```

E. Appendix: Lake Wheeler PLSR Model Median RMSE

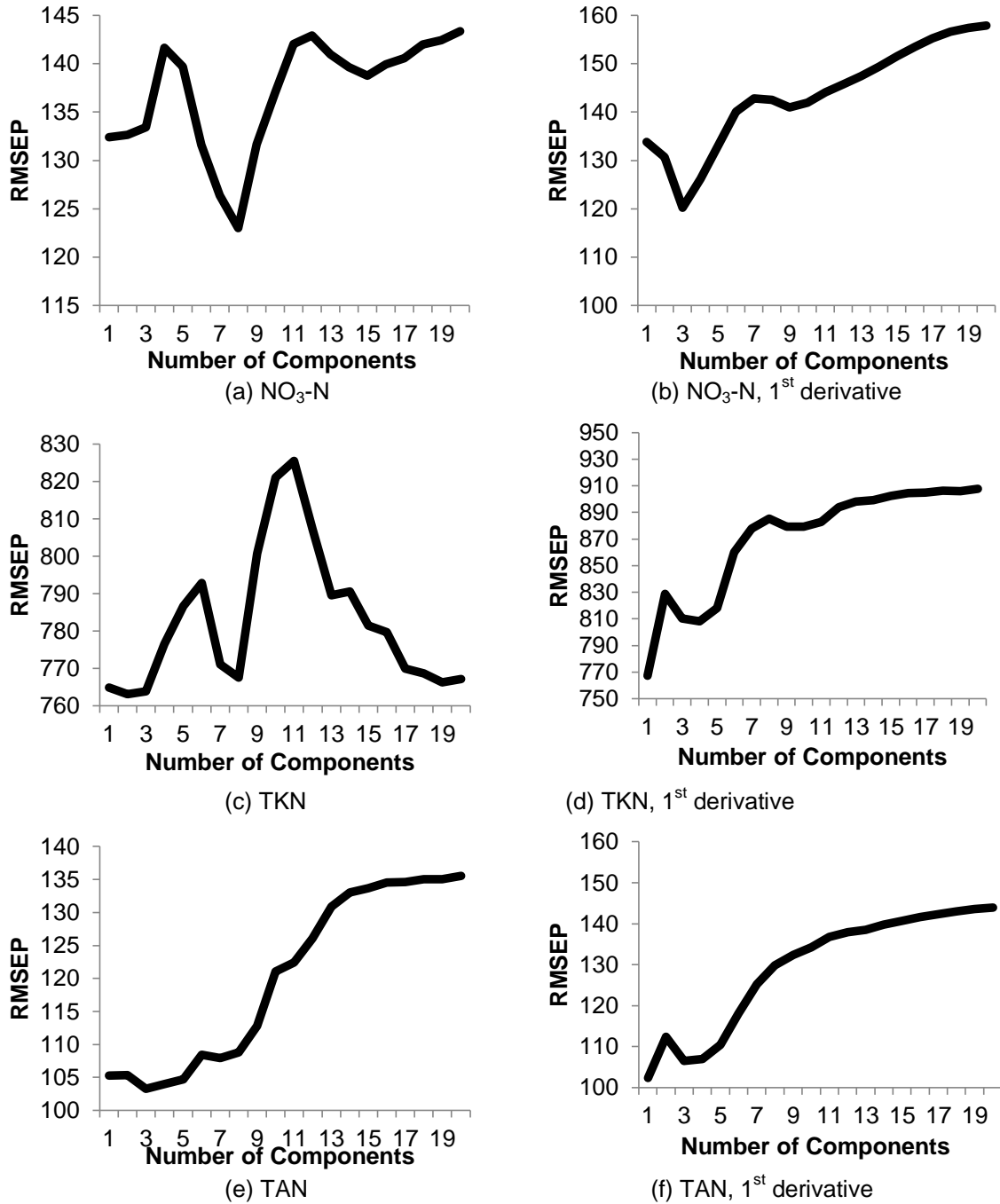
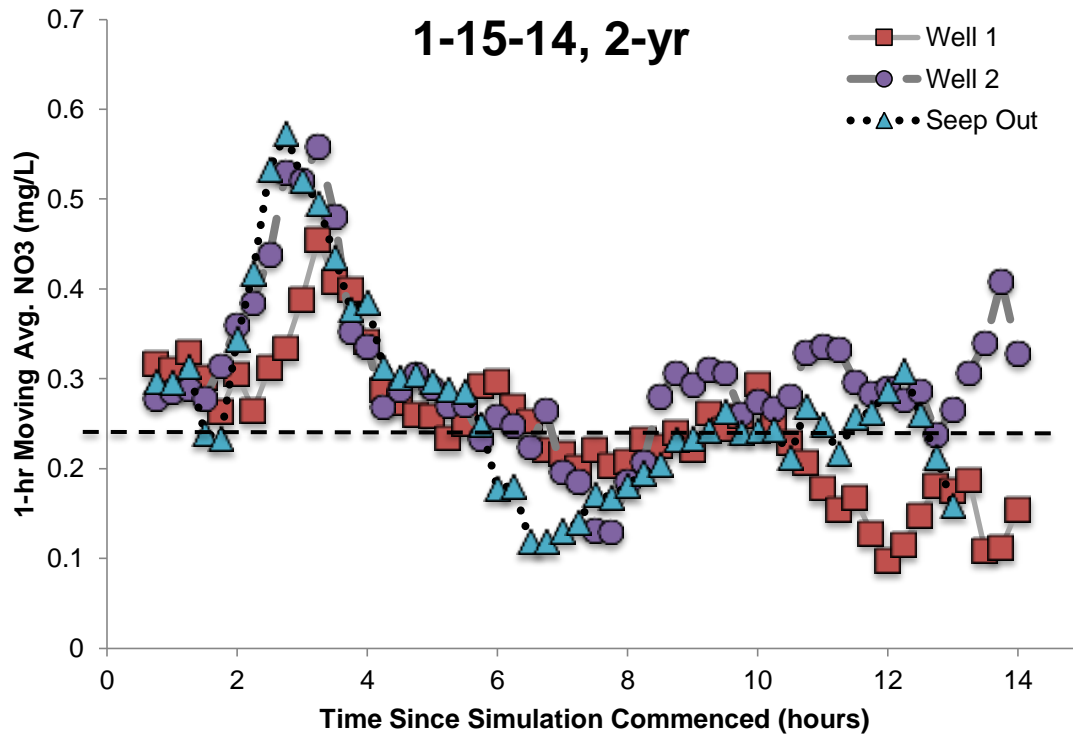
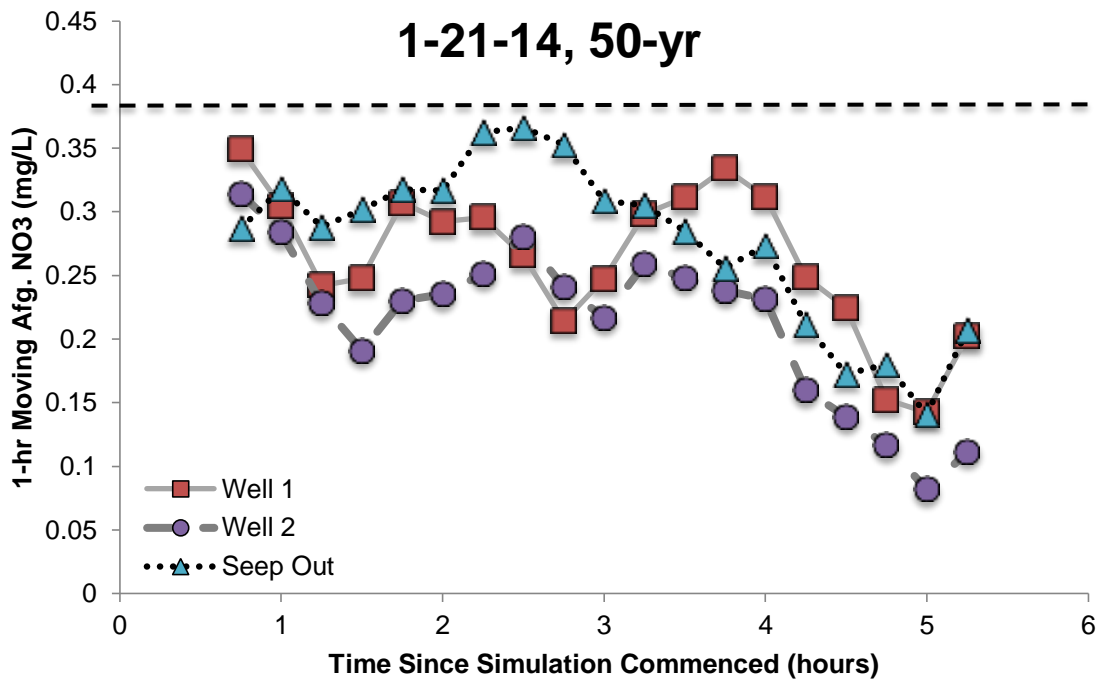
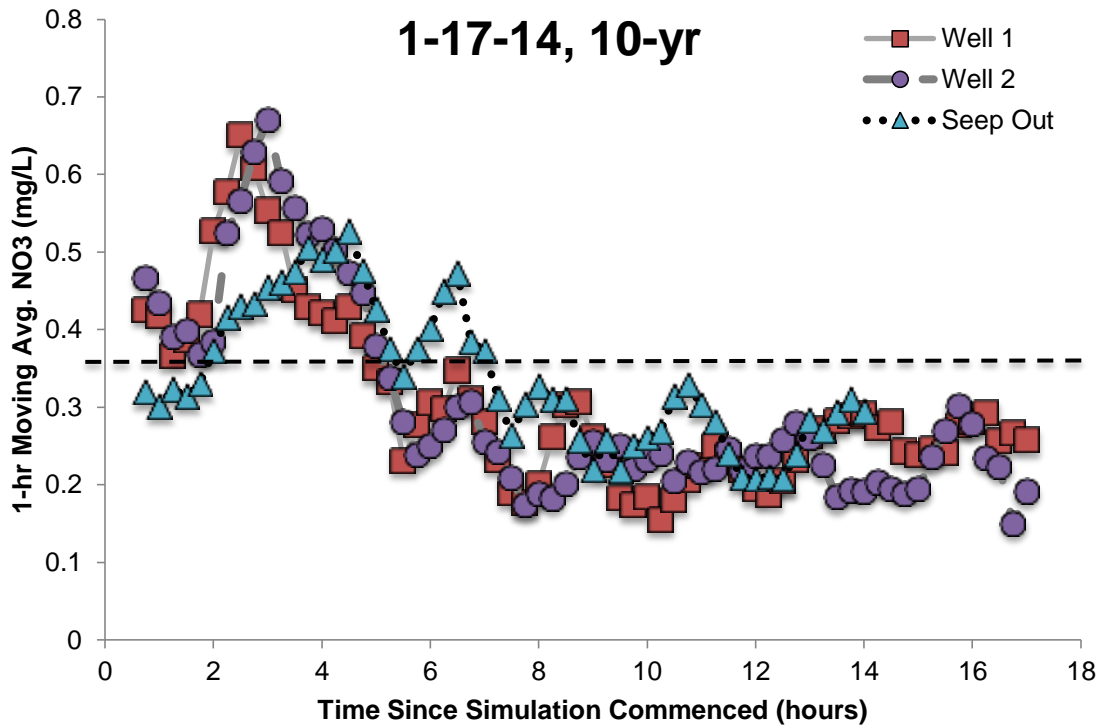


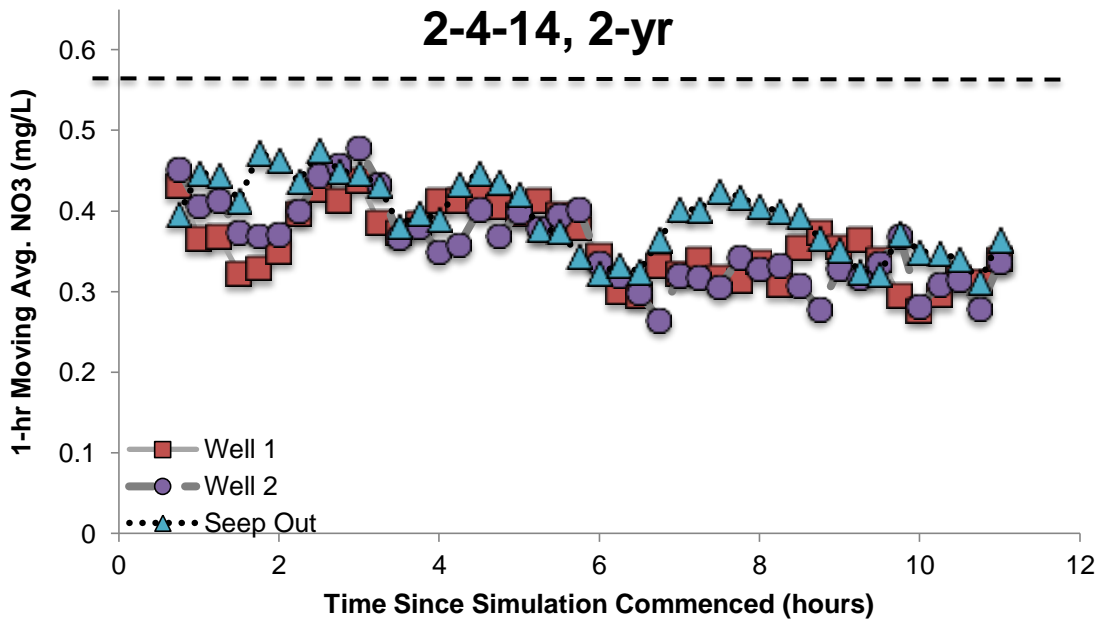
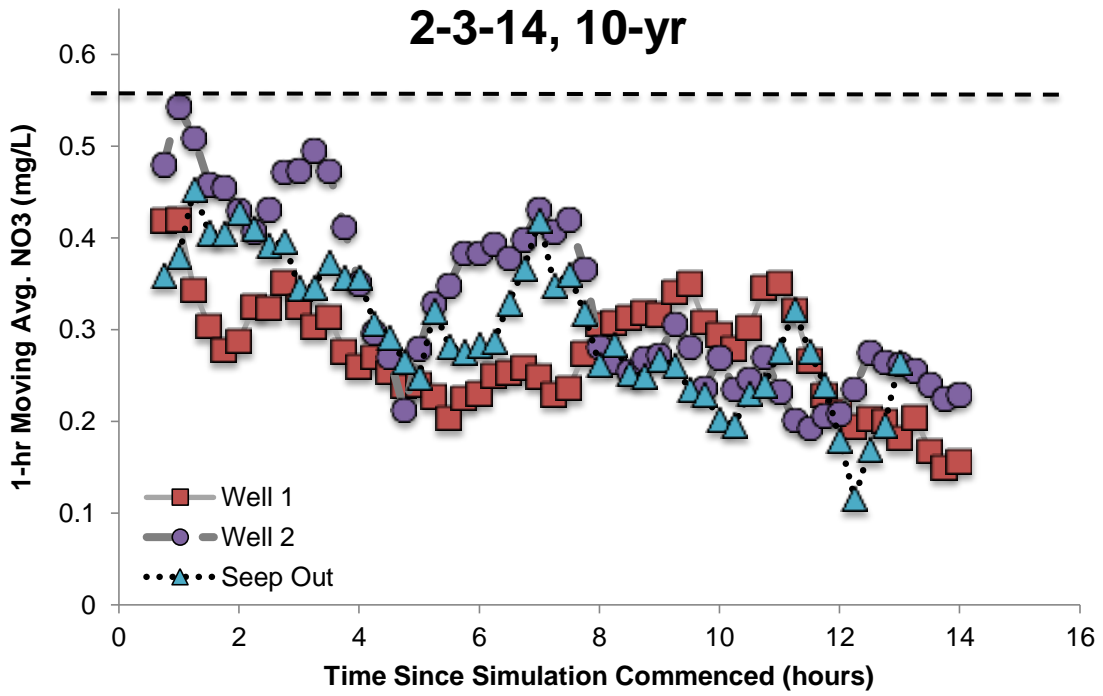
Figure E-1 Median RMSEP for PLSR models using different component numbers

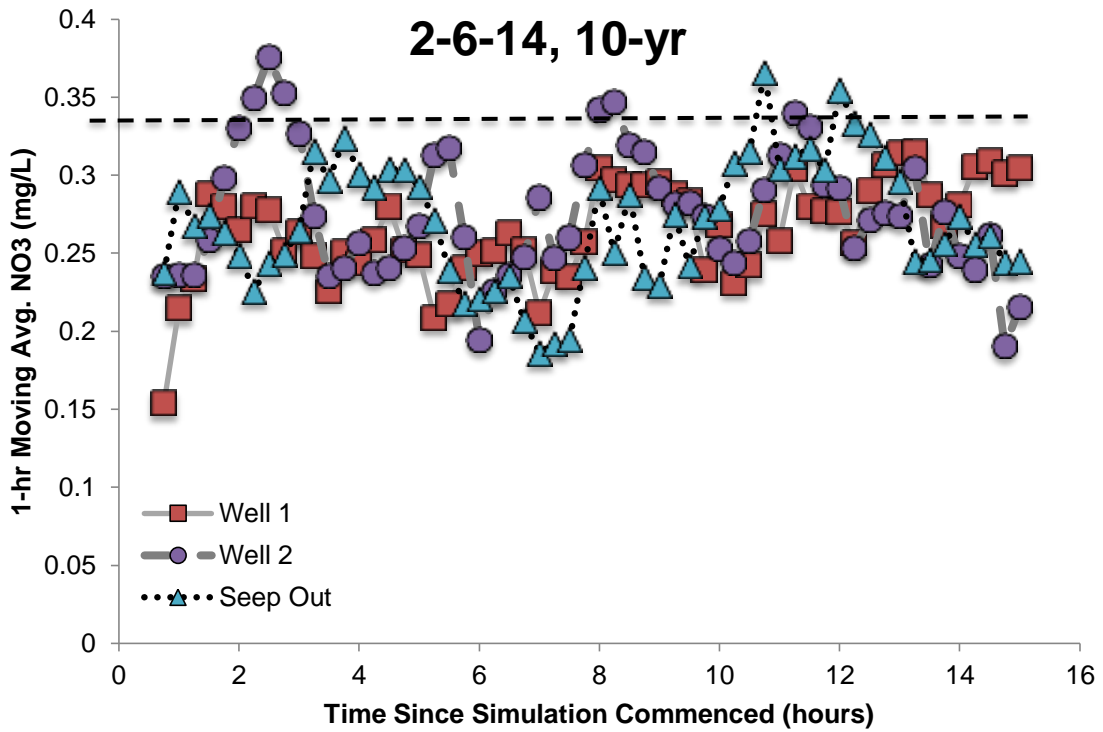
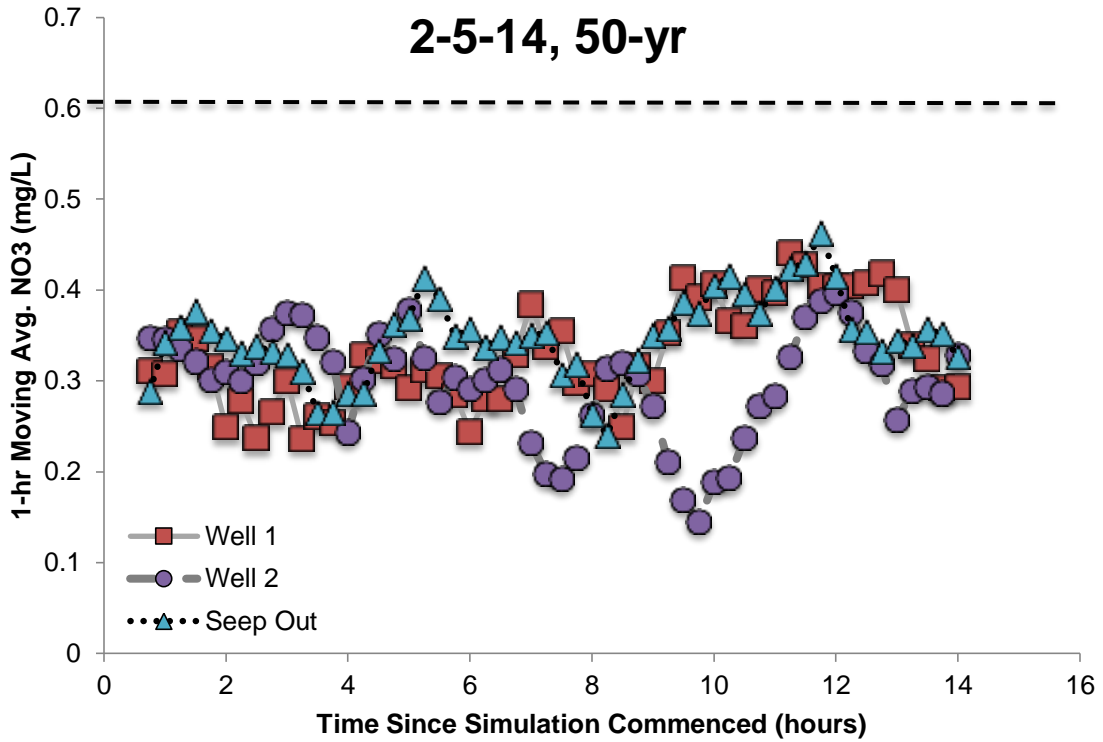
F. Appendix: Lake Wheeler Storm Simulation Data

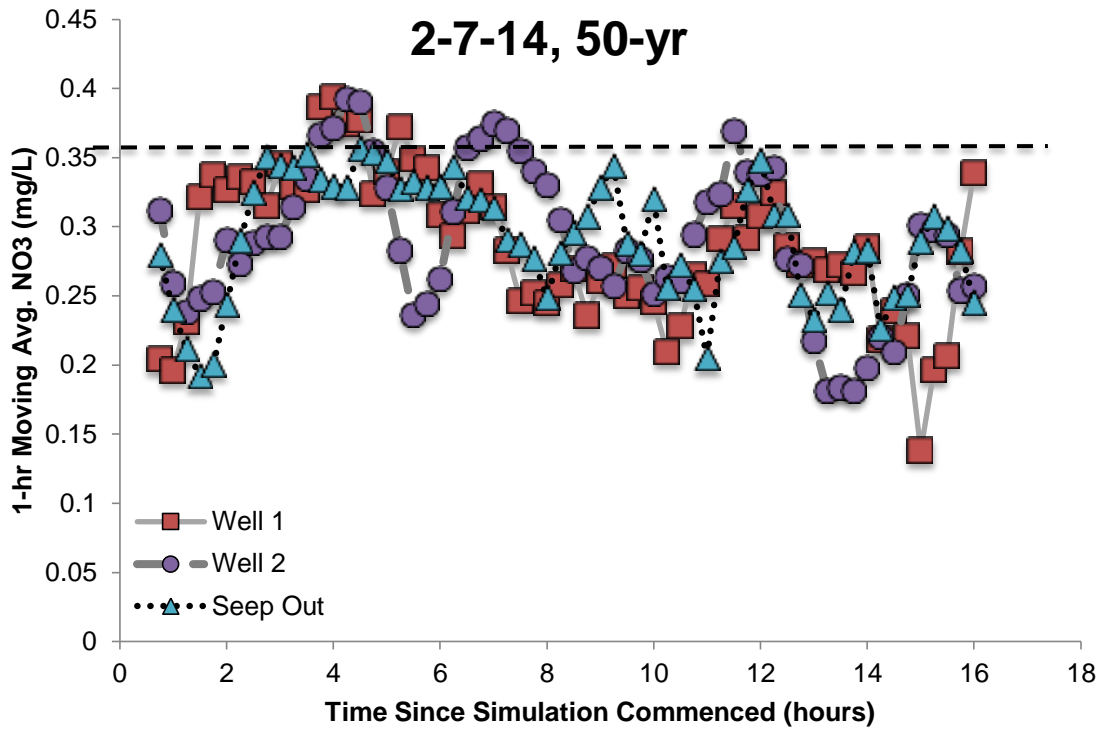
NO₃ concentration in wells for each storm simulation



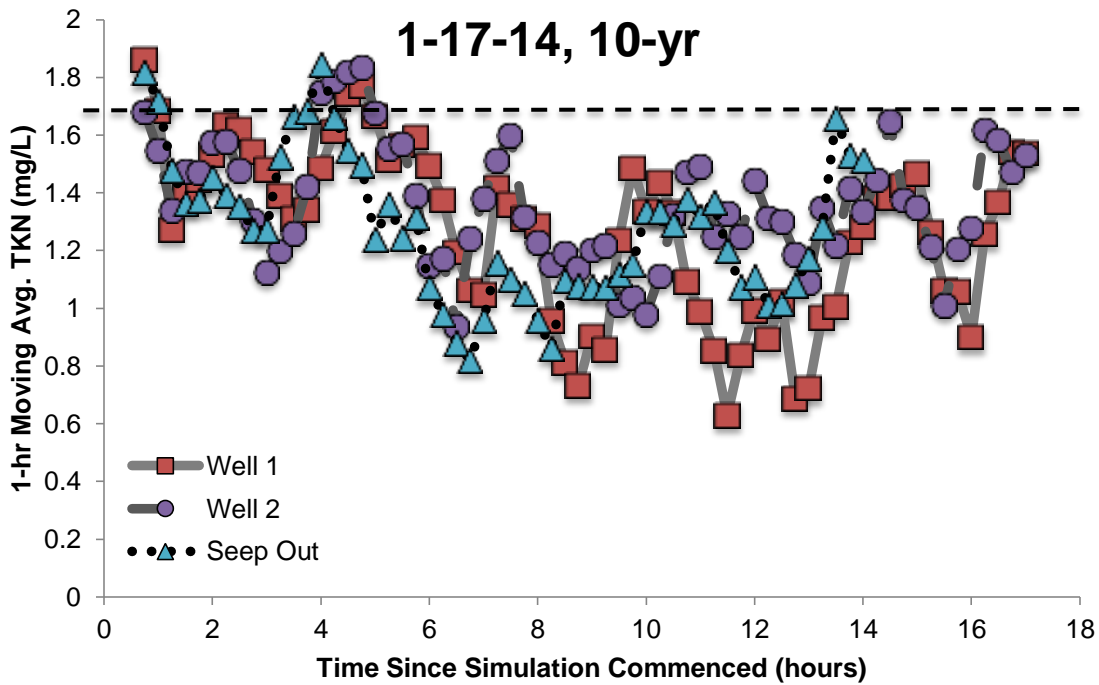
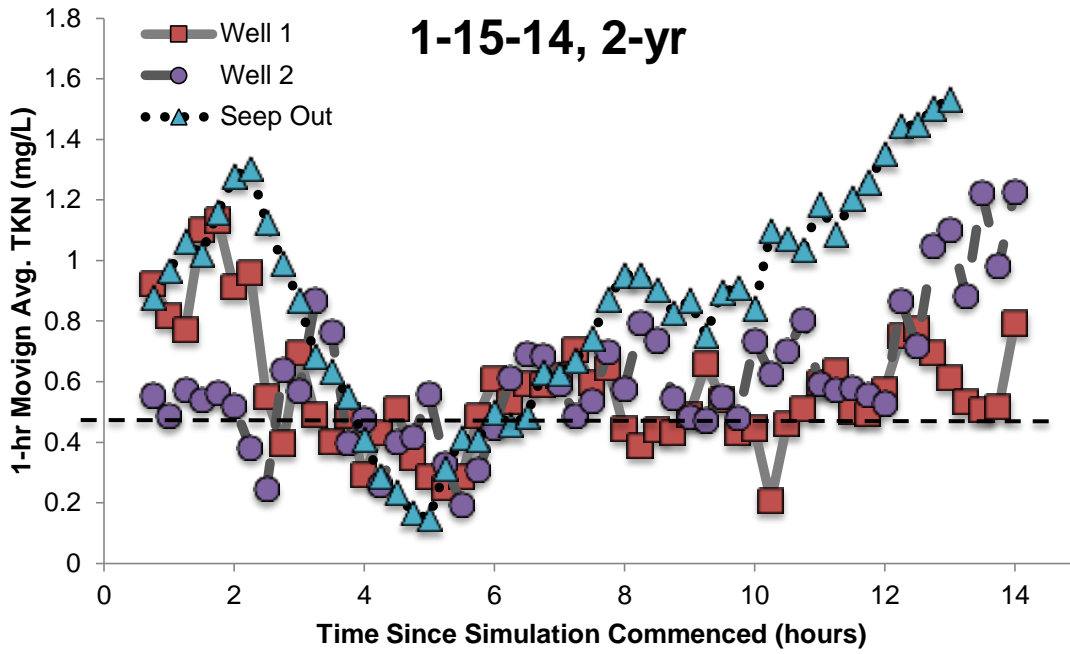


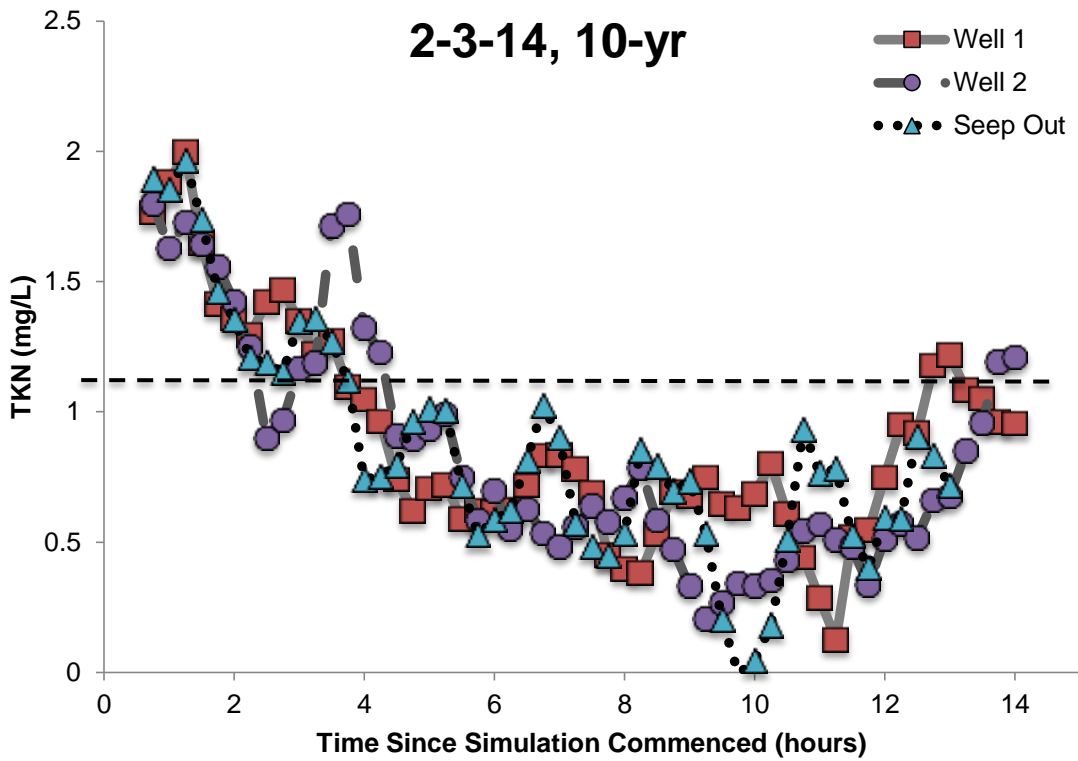
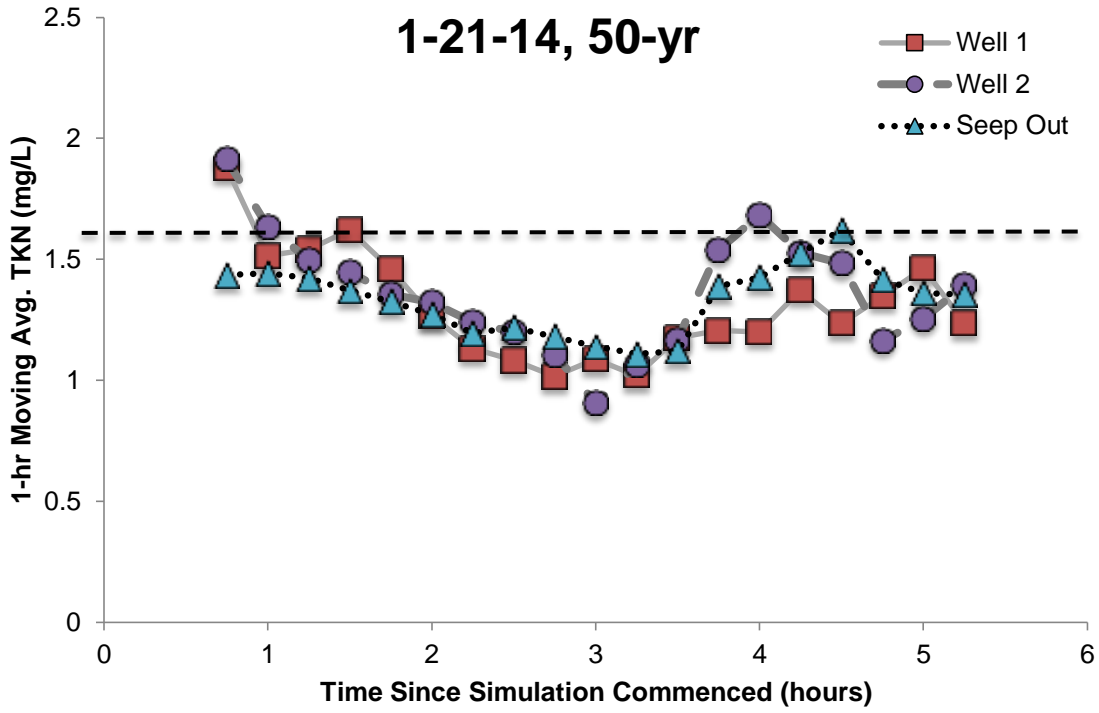


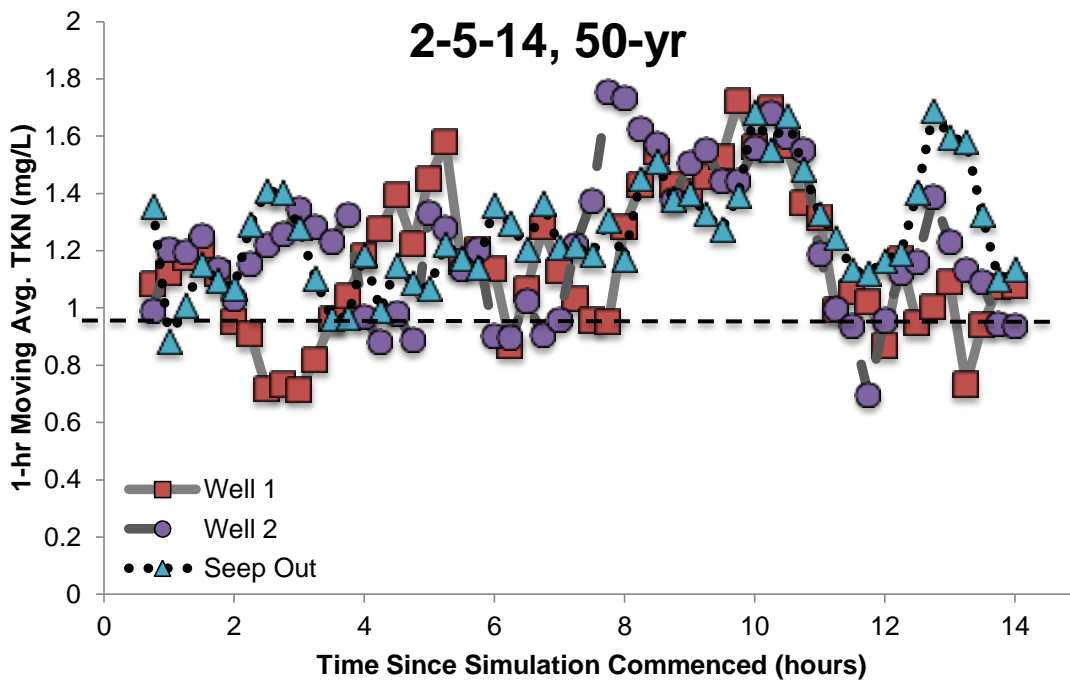
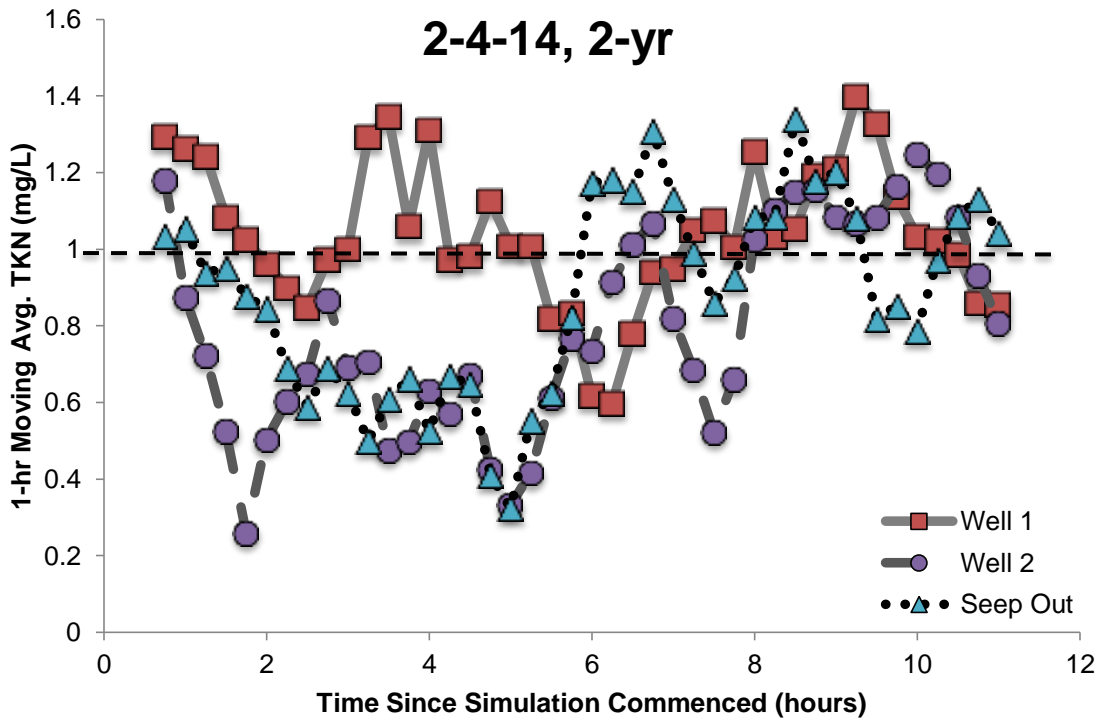


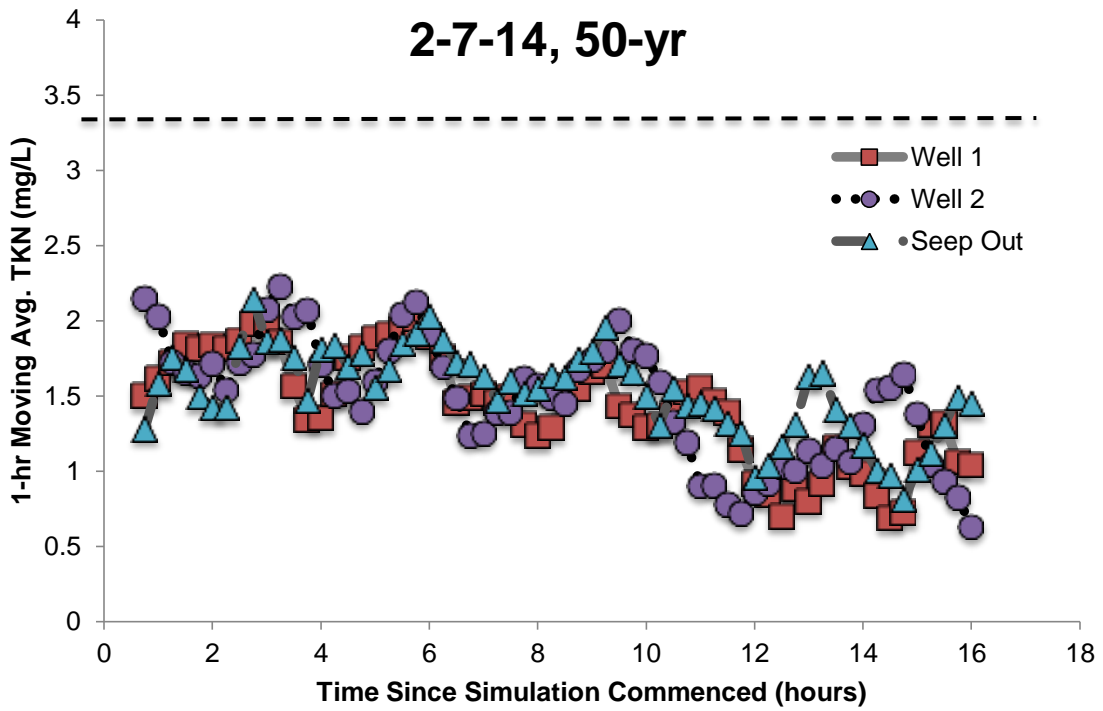
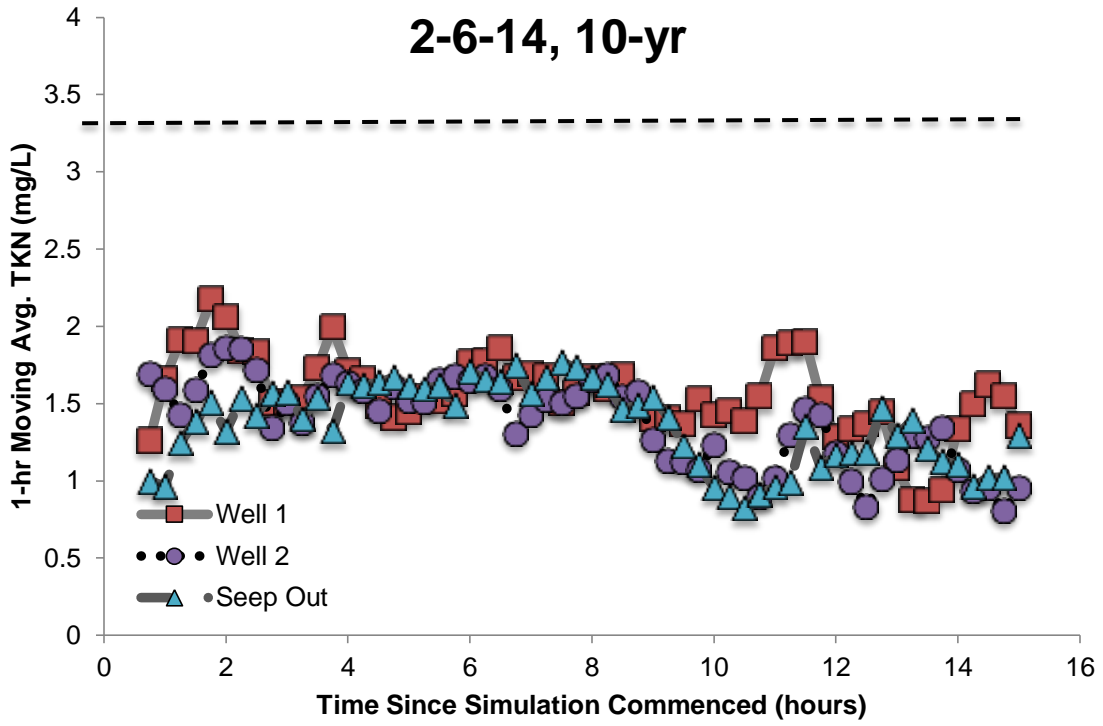


TKN concentration in wells for each storm simulation

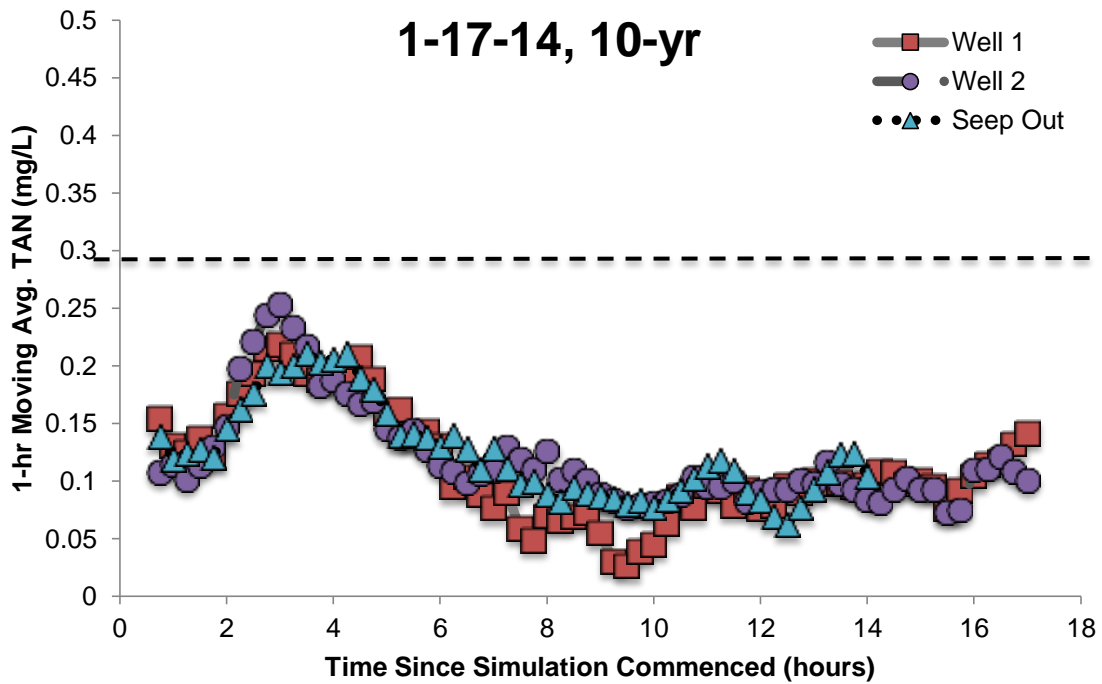
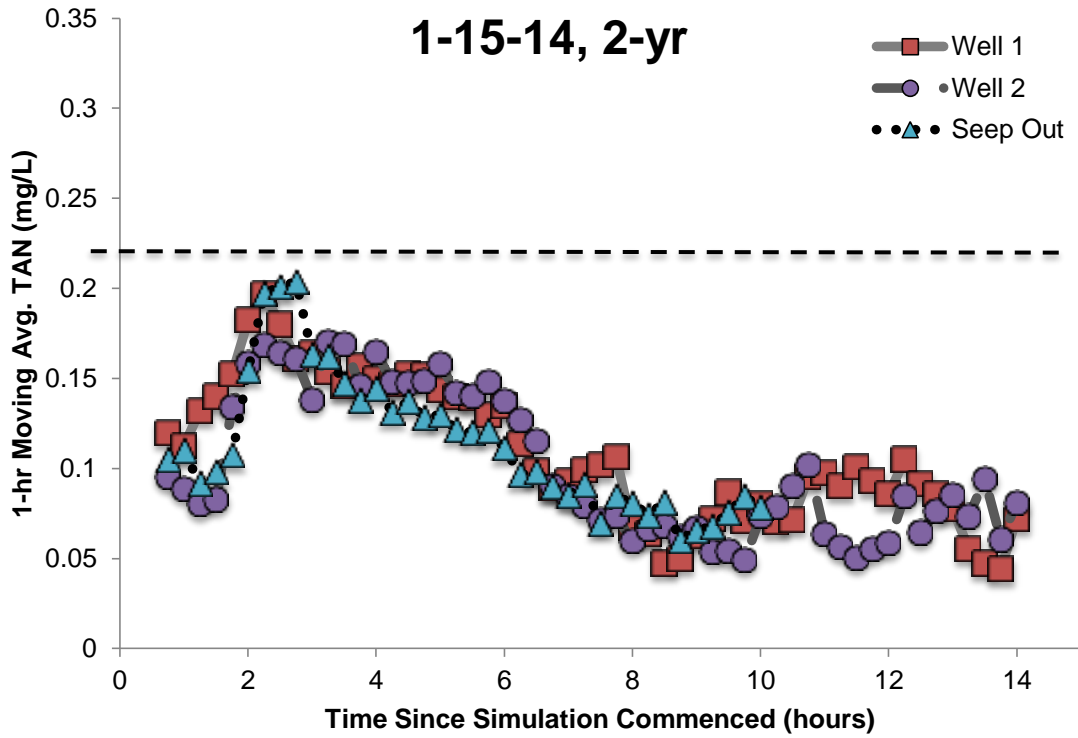


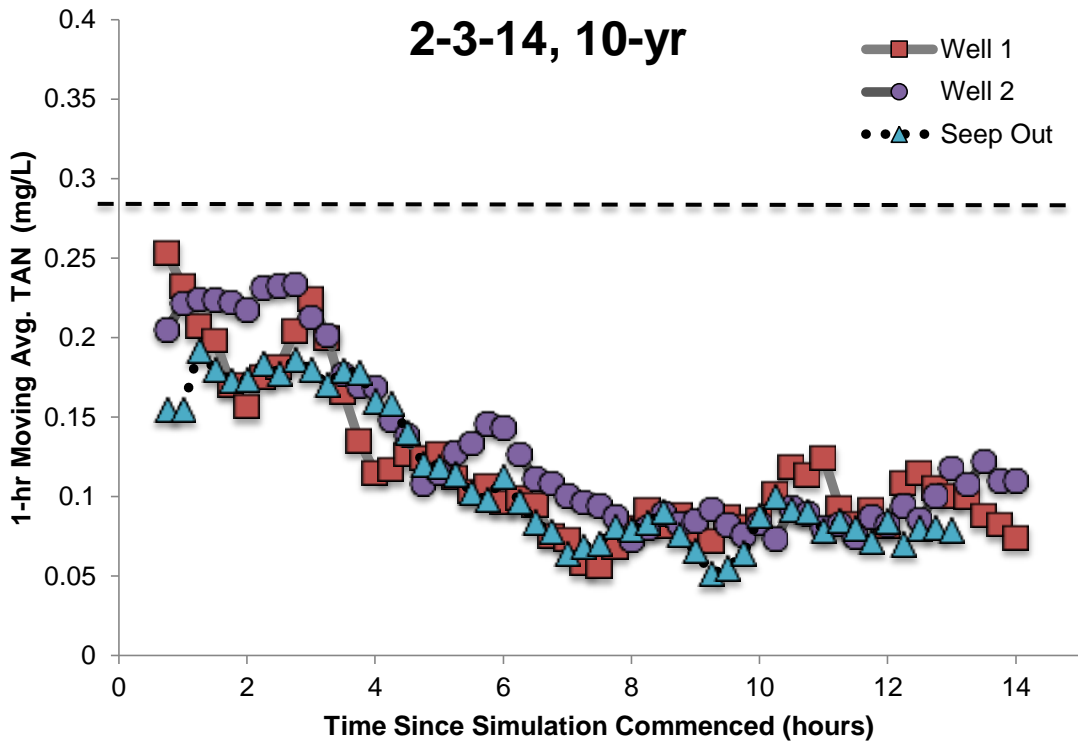
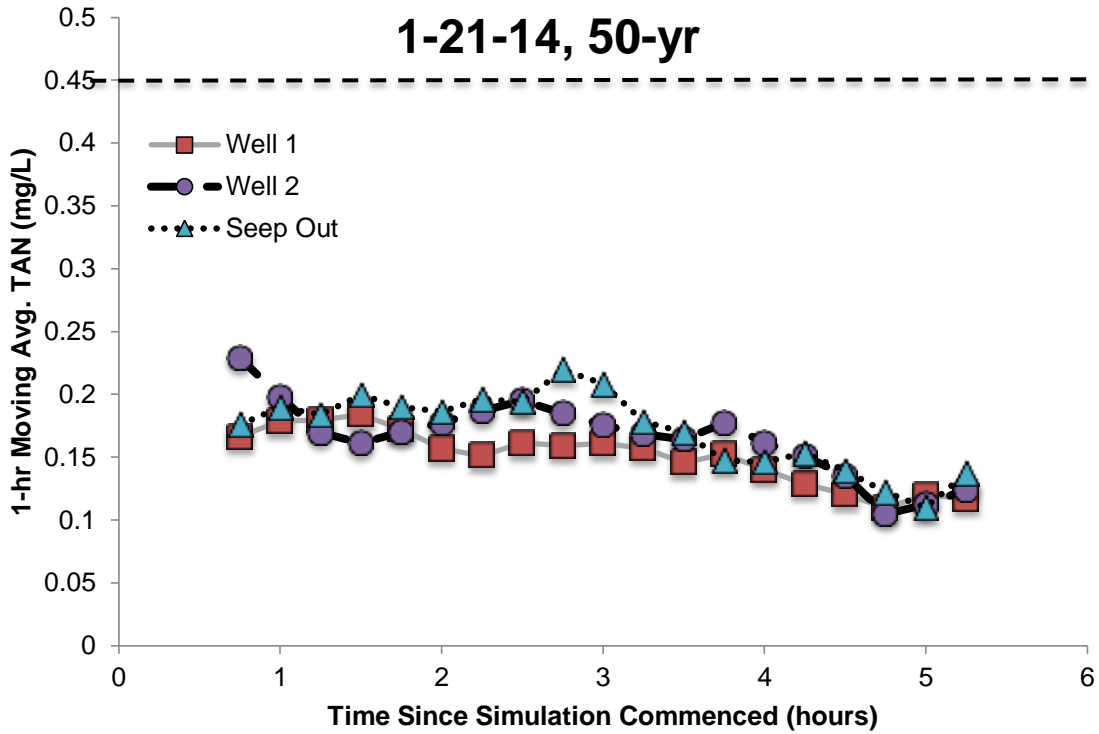


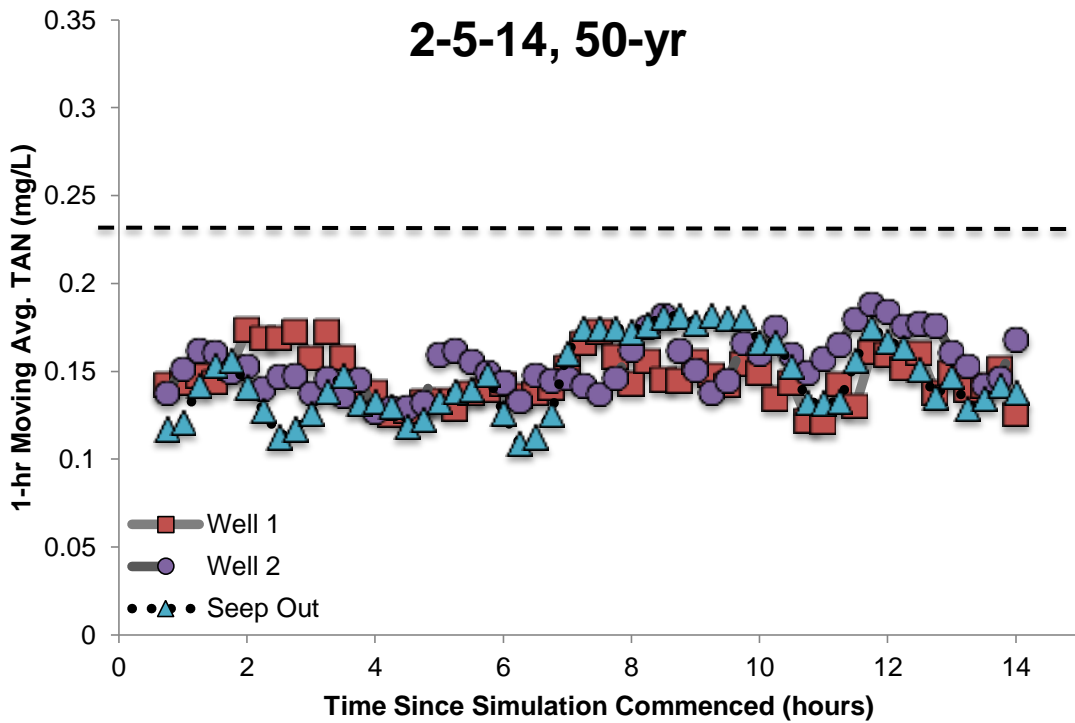
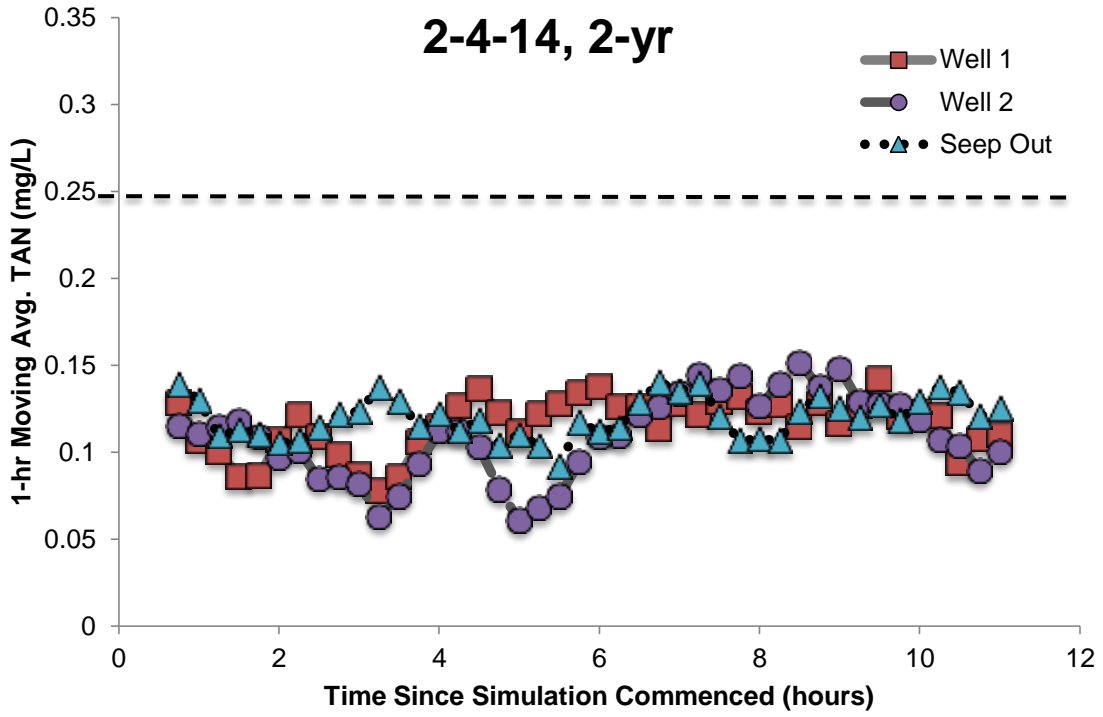


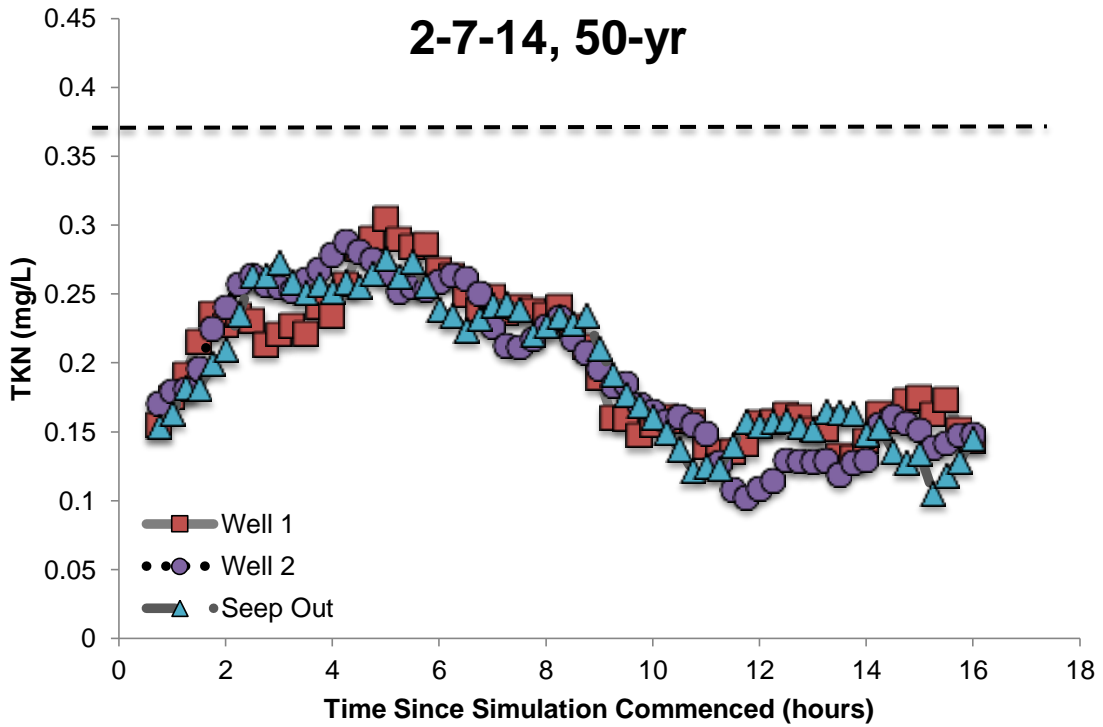
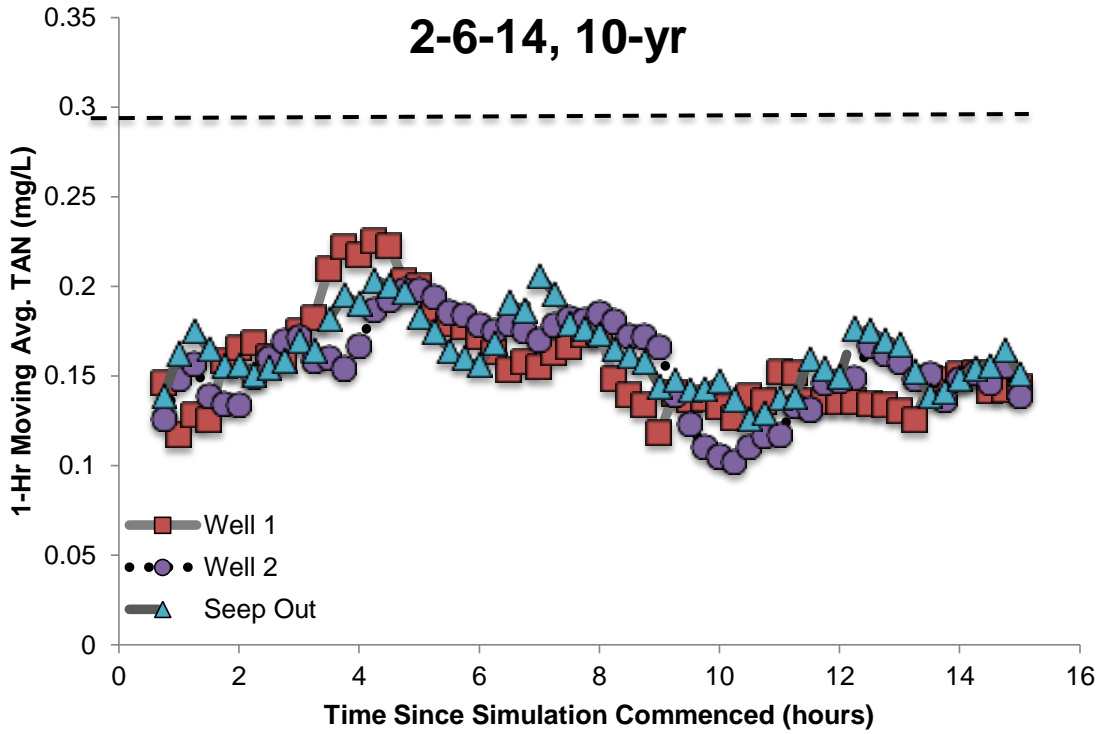


NO₃ concentration in wells for each storm simulation









G.Appendix: R-code for Lake Wheeler Subsurface

Analysis

Example RMSE for models using different numbers of components

```
pathD<-"~/Desktop/Lake Wheeler/NO3/"
filename<-"LkWhlr3_Cal1deriv.csv"
data<-read.table(file=paste(pathD,filename,sep=""),sep="," ,skip=1)
colnames(data) <- c( 'Date/Time', 'Status_0')
colnames(data)[3:(length(data)-2)]<-c(seq(200,750,2.5))

FP<-data[,-1:-2] #Remove NAs at low wavelengths
FP<-FP[,-(dim(FP)[2]-13):-dim(FP)[2]] #Remove NO3-N and NAs at high wavelengths
FP<-data.matrix(FP)
NO3<-data.matrix(data[dim(data)[2]-1])
Code<-(data[dim(data)[2]])

library(pls)
fit<-plsr(NO3~data.matrix(FP),ncomp=20,validation="CV") #PCR of Data
summary(fit)

#fit1<-lm(NO3[1:dim(NO3)[1]]~FP[,3]+FP[,6]+FP[,62]+FP[,82]+FP[,137]) #Linear model to
calculate NO3-N based on the wavelengths
#identified earlier

Pfit<-predict(fit,FP,ncomp=20,type=c("response"))

NO3P<-as.data.frame(matrix(0,1,dim(data)[1]))
NO3P<-as.data.frame(Pfit[1:dim(NO3)[1]])

plot(NO3,as.matrix(NO3P))

fit2<-lm(NO3~as.matrix(NO3P))
summary(fit2)

cex.lab=3
cex.axis=3
windowsFonts(times=windowsFont("Times"))
x11(width = 12, height = 10)
par(mar=c(6,6.5,1.5,1.5),family="times")
plot(as.matrix(NO3P),NO3,
      type="p",
      pch=16,
      cex=2,
```

```

#col=tim.colors(175)[round(CDOM)], #the whole trick is here
lwd=2, #I chose tim.colors as a
yaxt="n", #nice color theme
xaxt="n",
xlim=c(0,5),
ylim=c(0,5),
yaxs="i",
xaxs="i",
bty="n",
lty=1,
xlab="",
ylab=expression(Lab~Measured~NO[3]-N~(mg~L^-1)),
cex.lab=cex.lab,
cex.axis=cex.axis)
par(new=TRUE)
axis(2,cex.axis=cex.lab)
par(mgp=c(3,1.5,0),new=TRUE)
axis(1,cex.axis=cex.lab)
par(new=TRUE)
abline(0,1,lwd=2)
text(0.75,4.5,paste("R?=",signif(summary(fit2)$r.squared,digits=3),sep=""),cex=3)
title(xlab=expression(Predicted~NO[3]-N~(mg~L^-1)),cex.lab=3,mgp=c(5,1,0))

```

Example PLSR model code based on number of components

```

pathD<-"~/Desktop/Lake Wheeler/NO3/"
filename<-"LkWhlr3_Cal1deriv.csv"
data<-read.table(file=paste(pathD,filename,sep=""),sep="," ,skip=1)
#data<-data1[-nrow(data1),]
attach(data)

colnames(data) <- c( 'Date/Time', 'Status_0')
colnames(data)[3:(length(data)-2)]<-c(seq(200,750,2.5))

FP<-data[,-1:-2] #Remove NAs at low wavelengths
FP<-FP[,-(dim(FP)[2]-13):-dim(FP)[2]] #Remove NO3-N and NAs at high wavelengths
FP<-data.matrix(FP)
NO3<-data.matrix(data[dim(data)[2]-1])
Sal<-data.matrix(data[dim(data)[2]])

library(pls)

fit<-plsr(NO3~data.matrix(FP),ncomp=10) #PCR of Data
summary(fit)

setwd("~/Desktop/Lake Wheeler/NO3/")

```

```

pathD<-"~/Desktop/Lake Wheeler/Rscript/"
filename<-"LkWhlrAllPts1drv.fp"
data1<-read.table(file=paste(pathD,filename,sep=""),sep=" ",skip=2)
#data<-data1[-nrow(data1),]
#attach(data)

Xvalues<-as.numeric(seq(200,750,2.5))

colnames(data1) <- c('Date', 'Time', 'Status_0')
colnames(data1)[4:length(data1)]<-c(seq(200,750,2.5))

Date_<-substr(data1$Date, 1, 10)
T<-substr(data1$Time, 1, 8)
D<-paste(Date_,T,sep=" ")
Dat<-strptime(D, "%Y.%m.%d %H:%M:%S")

FP5<-data1[,-1:-3] #Remove NAs at low wavelengths
FP5<-FP5[-(dim(FP5)[2]-11):-dim(FP5)[2]] #Remove NO3-N and NAs at high wavelengths
FP5<-data.matrix(FP5)

NO3P<-as.data.frame(matrix(0,dim(data1)[1],2))
NO3P[,1]<-as.character(Dat, "%m/%d/%Y %H:%M:%S")

Pfit<-predict(fit,FP5,ncomp=10,type=c("response"))
NO3P[,2]<-as.data.frame(Pfit[1:dim(data1)[1]])

NO3P[is.na(NO3P$V2),"V2"]=0
NO3P[NO3P$V2<0.1,"V2"]=0.05

write.csv(NO3P,file="LkWhlr_NO3_1d_10c.csv",row.names=FALSE)

plot(Dat,NO3P[,2])

```

Example code for Nash-Sutcliffe goodness of fit

```
NSE(NO3_c8$Computed, NO3_c8$Observed)
```

R-code for water quality data analysis

```

### Subset by Well
NO3.r.1 <- subset(NO3.r, well==1)
NO3.r.2 <- subset(NO3.r, well==2)
NO3.r.3 <- subset(NO3.r, well==3)

TKN.r.1 <- subset(TKN.r, well==1)

```

```

TKN.r.2 <- subset(TKN.r, well==2)
TKN.r.3 <- subset(TKN.r, well==3)

TAN.r.1 <- subset(TAN.r, well==1)
TAN.r.2 <- subset(TAN.r, well==2)
TAN.r.3 <- subset(TAN.r, well==3)

## Concnetration differences over time
#Wilcoxon Rank Sum Test: NO3, Well 1
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.1, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.2, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.3, paired=TRUE)
> p = 0.3125
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.4, paired=TRUE)
> p = 0.1953
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.5, paired=TRUE)
> p = 0.0547
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.6, paired=TRUE)
> p = 0.0469
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.7, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.8, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.9, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.10, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.11, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.12, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.13, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.14, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.15, paired=TRUE)
> p = 0.25
wilcox.test(NO3.r.1$Inflow, NO3.r.1$hr.16, paired=TRUE)
> p = 0.5

#Wilcoxon Rank Sum Test: NO3, Well 2
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.1, paired=TRUE)
> p = 0.1284
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.2, paired=TRUE)
> p = 0.0391

```



```
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.3, paired=TRUE)
> p = 0.7422
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.4, paired=TRUE)
> p = 0.1953
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.5, paired=TRUE)
> p = 0.1094
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.6, paired=TRUE)
> p= 0.0313
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.7, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.8, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.9, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.10, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.11, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.12, paired=TRUE)
> p = 0.1563
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.13, paired=TRUE)
> p = 0.0625
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.14, paired=TRUE)
> p = 0.1563
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.15, paired=TRUE)
> p = 0.25
wilcox.test(NO3.r.2$Inflow, NO3.r.2$hr.16, paired=TRUE)
> p = 0.5
```

#Wilcoxon Rank Sum Test: NO3, Well 3

```
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.1, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.2, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.3, paired=TRUE)
> p = 0.4609
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.4, paired=TRUE)
> p = 0.1953
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.5, paired=TRUE)
> p = 0.1953
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.6, paired=TRUE)
> p = 0.0469
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.7, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.8, paired=TRUE)
> p = 0.0156
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.9, paired=TRUE)
```

```
> p = 0.0313
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.10, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.11, paired=TRUE)
> p = 0.0781
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.12, paired=TRUE)
> p = 0.0938
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.13, paired=TRUE)
> p = 0.0313
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.14, paired=TRUE)
> p = 0.125
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.15, paired=TRUE)
> p = 0.5
wilcox.test(NO3.r.3$Inflow, NO3.r.3$hr.16, paired=TRUE)
> p = 1
```

#Wilcoxon Rank Sum Test: TKN, Well 1

```
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.1, paired=TRUE)
> p = 0.7422
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.2, paired=TRUE)
> p = 0.5469
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.3, paired=TRUE)
> p = 0.0781
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.4, paired=TRUE)
> p = 0.0781
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.5, paired=TRUE)
> p = 0.1094
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.6, paired=TRUE)
> p = 0.1094
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.7, paired=TRUE)
> p = 0.1563
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.8, paired=TRUE)
> p = 0.0781
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.9, paired=TRUE)
> p = 0.1562
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.10, paired=TRUE)
> p = 0.2969
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.11, paired=TRUE)
> p = 0.1094
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.12, paired=TRUE)
> p = 0.0938
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.13, paired=TRUE)
> p = 0.4375
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.14, paired=TRUE)
> p = 0.1563
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.15, paired=TRUE)
> p = 0.25
```

```
wilcox.test(TKN.r.1$Inflow, TKN.r.1$hr.16, paired=TRUE)
> p = 0.5
```

```
#Wilcoxon Rank Sum Test: TKN, Well 2
```

```
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.1, paired=TRUE)
> p = 0.9453
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.2, paired=TRUE)
> p = 0.1953
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.3, paired=TRUE)
> p = 0.0781
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.4, paired=TRUE)
> p = 0.25
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.5, paired=TRUE)
> p = 0.0156
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.6, paired=TRUE)
> p = 0.0469
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.7, paired=TRUE)
> p = 0.1094
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.8, paired=TRUE)
> p = 0.2188
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.9, paired=TRUE)
> p = 0.2188
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.10, paired=TRUE)
> p = 0.1563
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.11, paired=TRUE)
> p = 0.2188
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.12, paired=TRUE)
> p = 0.0625
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.13, paired=TRUE)
> p = 0.2188
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.14, paired=TRUE)
> p = 0.2135
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.15, paired=TRUE)
> p = 0.25
wilcox.test(TKN.r.2$Inflow, TKN.r.2$hr.16, paired=TRUE)
> p = 0.5
```

```
#Wilcoxon Rank Sum Test: TKN, Well 3
```

```
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.1, paired=TRUE)
> p = 1
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.2, paired=TRUE)
> p = 0.3125
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.3, paired=TRUE)
> p = 0.1953
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.4, paired=TRUE)
> p = 0.0391
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.5, paired=TRUE)
```

```
> p = 0.0156
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.6, paired=TRUE)
> p = 0.0469
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.7, paired=TRUE)
> p = 0.375
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.8, paired=TRUE)
> p = 0.1563
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.9, paired=TRUE)
> p = 0.2188
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.10, paired=TRUE)
> p = 0.1563
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.11, paired=TRUE)
> p = 0.5781
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.12, paired=TRUE)
> p = 0.3125
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.13, paired=TRUE)
> p = 0.4375
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.14, paired=TRUE)
> p = 0.25
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.15, paired=TRUE)
> p = 0.5
wilcox.test(TKN.r.3$Inflow, TKN.r.3$hr.16, paired=TRUE)
> p = 1
```

#Wilcoxon Rank Sum Test: TAN, Well 1

```
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.1, paired=TRUE)
> p = 0.0391
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.2, paired=TRUE)
> p = 0.0391
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.3, paired=TRUE)
> p = 0.0547
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.4, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.5, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.6, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.7, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.8, paired=TRUE)
> p = 0.0469
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.9, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.10, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.11, paired=TRUE)
> p = 0.0313
```

```
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.12, paired=TRUE)
> p = 0.0938
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.13, paired=TRUE)
> p = 0.0625
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.14, paired=TRUE)
> p = 0.0625
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.15, paired=TRUE)
> p = 0.25
wilcox.test(TAN.r.1$Inflow, TAN.r.1$hr.16, paired=TRUE)
> p = 0.5
```

```
#Wilcoxon Rank Sum Test: TAN, Well 2
```

```
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.1, paired=TRUE)
> p = 0.0234
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.2, paired=TRUE)
> p = 0.0391
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.3, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.4, paired=TRUE)
> p = 0.0547
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.5, paired=TRUE)
> p = 0.0547
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.6, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.7, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.8, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.9, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.10, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.11, paired=TRUE)
> p = 0.0467
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.12, paired=TRUE)
> p = 0.0625
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.13, paired=TRUE)
> p = 0.0938
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.14, paired=TRUE)
> p = 0.0625
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.15, paired=TRUE)
> p = 0.25
wilcox.test(TAN.r.2$Inflow, TAN.r.2$hr.16, paired=TRUE)
> p = 0.5
```

```
#Wilcoxon Rank Sum Test: TAN, Well 2
```

```
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.1, paired=TRUE)
```

```

> p = 0.0156
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.2, paired=TRUE)
> p= 0.0234
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.3, paired=TRUE)
> p = 0.1484
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.4, paired=TRUE)
> p = 0.1094
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.5, paired=TRUE)
> p = 0.0547
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.6, paired=TRUE)
> p = 0.0467
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.7, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.8, paired=TRUE)
> p = 0.0469
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.9, paired=TRUE)
> p = 0.0313
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.10, paired=TRUE)
> p = 0.0469
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.11, paired=TRUE)
> p = 0.0469
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.12, paired=TRUE)
> p = 0.1563
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.13, paired=TRUE)
> p = 0.1563
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.14, paired=TRUE)
> p = 0.125
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.15, paired=TRUE)
> p = 0.5
wilcox.test(TAN.r.3$Inflow, TAN.r.3$hr.16, paired=TRUE)
> p = 1

## Test for ordered significance, NO3
x.NO3.1 = c(NO3.r$hr.12, NO3.r$hr.10, NO3.r$hr.8, NO3.r$hr.6, NO3.r$hr.4, NO3.r$hr.2)
grps.NO3.1 = c(rep(1,24), rep(2,24), rep(3,24), rep(4,24), rep(5,24), rep(6,24))

trtmeans.NO3.1 = getmeans(x.NO3.1, grps.NO3.1)
nn.NO3.1 <- table(factor(grps.NO3.1)) #size of each treatment group
k.NO3.1 <- length(trtmeans.NO3.1) #number of treatments

### based on rank-sum statistic
JT.ranksum(x.NO3.1, grps.NO3.1, k.NO3.1, R=1000)
> p = 0.087

####based on Mann-Whitney statistic
JT.MW(x.NO3.1, grps.NO3.1, k.NO3.1, R=1000)
> p = 0.099

```

```

## Test for ordered significance, TKN
x.TKN.1 = c(TKN.r$hr.12, TKN.r$hr.10, TKN.r$hr.8, TKN.r$hr.6, TKN.r$hr.4, TKN.r$hr.2)
grps.TKN.1 = c(rep(1,24), rep(2,24), rep(3,24), rep(4,24), rep(5,24), rep(6,24))

trtmeans.TKN.1 = getmeans(x.TKN.1, grps.TKN.1)
nn.TKN.1 <- table(factor(grps.TKN.1)) #size of each treatment group
k.TKN.1 <- length(trtmeans.TKN.1) #number of treatments

### based on rank-sum statistic
JT.ranksum(x.TKN.1, grps.TKN.1, k.TKN.1, R=1000)
> p = 0.04

###based on Mann-Whitney statistic
JT.MW(x.TKN.1, grps.TKN.1, k.TKN.1, R=1000)
> p = 0.038

## Test for ordered significance, TAN
x.TAN.1 = c(TAN.r$hr.12, TAN.r$hr.10, TAN.r$hr.8, TAN.r$hr.6, TAN.r$hr.4, TAN.r$hr.2)
grps.TAN.1 = c(rep(1,24), rep(2,24), rep(3,24), rep(4,24), rep(5,24), rep(6,24))

trtmeans.TAN.1 = getmeans(x.TAN.1, grps.TAN.1)
nn.TAN.1 <- table(factor(grps.TAN.1)) #size of each treatment group
k.TAN.1 <- length(trtmeans.TAN.1) #number of treatments

### based on rank-sum statistic
JT.ranksum(x.TAN.1, grps.TAN.1, k.TAN.1, R=1000)
> p = 0.05

###based on Mann-Whitney statistic
JT.MW(x.TAN.1, grps.TAN.1, k.TAN.1, R=1000)
> p = 0.058

```

H. Appendix: Ecosystem Service Analysis Data

Table H-1 Select ecosystem service values for each RSC site

Site	SWIndex	Richness	Habitat	Recreation	Education	Cultural
AI	1.47	7.00	0.5	2.33	0.00	1.17
CS	1.96	10.00	0.5	2.00	0.00	1.00
CB	1.16	8.00	1.0	2.67	0.67	1.67
BR	na	na	0.5	2.33	0.00	1.00
CR	1.53	11.00	3.0	3.00	0.67	1.83
CS	1.56	9.00	2.0	2.00	0.00	1.00
CH	1.95	9.00	1.0	2.33	0.33	1.33
CH	1.09	5.00	3.0	2.33	0.67	1.50
HP	2.27	14.00	1.0	1.33	0.00	0.67
WE	1.78	18.00	3.0	3.33	1.00	2.17
HP	1.55	7.00	2.0	1.33	0.00	0.67
WE	1.42	6.00	4.0	3.33	1.00	2.17
HB	1.55	19.00	4.0	3.33	1.67	2.50
HB	0.95	8.00	5.0	3.00	1.67	2.33
MD	0.96	3.00	5.0	1.67	0.67	1.17
UM	1.71	9.00	4.0	3.67	2.67	3.17

Table H-2 Carbon and microbial biomass data for each transect point

Site	% Tot Carbon	Total Areal Carbon g C m ⁻²	Total Carbon g C kg ⁻¹	MB.C g kg ⁻¹	MB.N g kg ⁻¹	C:N	MBC Quotient
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
AL	0.00	0	0.00	0.00	0.00		na
CS	0.34	842	3.35	0.16	0.04	3.96	0.04
CS	2.46	3923	24.60	0.07	0.01	4.76	0.00
CS	1.96	3927	19.63	0.24	0.07	3.58	0.01
CS	0.18	445	1.80	0.13	0.04	3.52	0.06
CS	0.70	884	7.00	0.16	0.03	5.13	0.04
CS	1.51	2792	15.08	0.15	0.04	4.19	0.01
CS	1.34	2375	13.43	0.11	0.03	4.02	0.01
CS	0.38	918	3.75	0.00	0.00		na
CS	1.99	161	19.90	0.12	0.03	3.63	0.00
CB	1.58	2527	15.75	0.00	0.00		0.00
CB	0.56	960	5.55	0.05	0.00	11.83	0.01
CB	4.01	3537	40.10	0.15	0.03	4.90	0.00
CB	2.41	2842	24.05	0.18	0.03	5.94	0.01
CB	2.27	4276	22.68	0.23	0.03	7.53	0.01
CB	0.16	358	1.63	0.00	0.00		na
CB	1.19	1436	11.90	0.17	0.03	6.92	0.03
CB	1.88	3004	18.75	0.00	0.00		na
Cr	0.76	675	7.58	0.14	0.02	6.48	0.01
Cr	1.08	745	10.80	0.04	0.00	11.40	0.00
Cr	0.62	1091	6.18	0.06	0.01	7.55	0.01
Cr	0.69	1170	19.05	0.26	0.04	6.74	0.01
Cr	0.00	0	0.00	0.00	0.00		na
Cr	1.57	1086	15.68	0.12	0.03	4.14	0.01
Cr	1.26	2501	12.58	0.33	0.05	6.05	0.02
Cr	0.00	0	0.00	0.23	0.03	6.60	na

Site	% Tot Carbon	Total Areal Carbon g C m ⁻²	Total Carbon g C kg ⁻¹	MB.C g kg ⁻¹	MB.N g kg ⁻¹	C:N	MBC Quotient
Cr	3.25	3427	32.50	0.12	0.02	6.19	0.00
CS	0.41	861	4.05	0.00	0.00		na
CS	0.73	1052	7.25	0.11	0.02	6.65	0.02
CS	1.17	2277	11.65	0.20	0.05	4.29	0.02
CS	1.11	2381	11.10	0.16	0.04	4.35	0.01
CS	0.00	0	0.00	0.00	0.00		0.00
CS	2.90	3659	29.03	0.07	0.02	4.27	0.00
CS	0.77	1560	7.68	0.32	0.08	4.08	0.04
CS	1.97	3842	19.65	0.15	0.02	6.60	0.01
CS	1.25	2527	12.53	0.00	0.01		na
CH	1.66	3551	16.63	0.15	0.05	3.07	0.01
CH	1.52	2799	15.20	0.00	0.00		na
CH	0.80	1828	7.98	0.10	0.03	3.30	0.01
CH	1.73	2714	17.30	0.07	0.03	2.55	0.00
CH	1.60	2854	15.98	0.21	0.06	3.19	0.01
CH	2.18	4161	21.78	0.16	0.04	4.06	0.01
CH	3.93	4683	39.28	0.00	0.00		na
CH	1.69	3405	16.90	0.02	0.01	2.13	0.00
CH	1.08	2475	10.75	0.01	0.00	4.50	0.00
CH	1.49	2526	14.93	0.08	0.02	5.58	0.00
CH	1.18	1728	11.80	0.11	0.03	4.10	0.01
CH	1.58	3214	15.78	0.11	0.02	4.84	0.01
CH	3.18	5703	31.80	0.38	0.08	4.92	0.01
CH	0.00	0	0.00	0.00	0.00		na
CH	0.00	0	0.00	0.04	0.01	3.64	na
CH	4.93	4438	49.28	0.15	0.04	3.62	0.00
CH	0.92	1696	9.20	0.08	0.02	4.96	0.01
CH	2.68	4140	26.80	0.21	0.05	4.35	0.01
HP	2.94	6228	29.35	0.31	0.12	2.59	0.01
HP	11.32	14729	113.20	0.34	0.10	3.39	0.00
HP	1.65	3780	16.45	0.15	0.05	3.16	0.01
HP	1.13	2511	11.28	0.12	0.03	3.98	0.01
HP	13.34	14225	133.35	0.00	0.00		na
HP	5.31	7983	47.40	0.02	0.01	1.67	0.00
HP	2.06	3639	20.58	0.22	0.06	3.80	0.01
HP	4.73	4602	47.30	0.11	0.03	4.17	0.00
HP	4.70	7498	46.98	0.18	0.05	3.51	0.00

Table H-2 (continued)

Site	% Tot Carbon	Total Areal Carbon g C m ⁻²	Total Carbon g C kg ⁻¹	MB.C g kg ⁻¹	MB.N g kg ⁻¹	C:N	MBC Quotient
WE	1.42	2374	14.23	0.20	0.05	3.66	0.02
WE	0.00	0	0.00	0.00	0.00		na
WE	0.56	918	5.55	0.49	0.16	3.05	0.07
WE	0.57	1412	5.70	0.16	0.06	2.66	0.02
WE	0.00	0	0.00	0.12	0.03	4.00	na
WE	1.43	2552	14.33	0.34	0.10	3.51	0.02
WE	0.34	1129	3.38	0.00	0.00		0.00
WE	0.00	0	0.00	0.18	0.06	3.00	na
WE	0.25	669	2.50	0.30	0.09	3.18	0.10
HP	2.12	3864	21.20	0.16	0.04	4.02	0.01
HP	10.39	8728	103.93	0.63	0.11	5.53	0.01
HP	1.33	3337	13.33	0.16	0.04	3.97	0.01
HP	0.89	1753	8.93	0.22	0.04	4.99	0.02
HP	9.18	4844	91.80	0.10	0.00		0.00
HP	1.20	2142	12.00	0.25	0.04	5.98	0.02
HP	1.26	2181	12.58	0.24	0.05	5.14	0.02
HP	5.13	6341	51.25	0.27	0.04	6.60	0.00
HP	3.24	4981	32.43	0.18	0.04	4.14	0.00
WE	0.44	787	4.43	0.13	0.02	6.34	0.02
WE	2.91	2973	29.13	0.14	0.02	6.70	0.01
WE	1.80	1647	18.03	0.78	0.11	6.77	0.04
WE	0.23	324	2.28	0.21	0.04	5.11	0.21
WE	0.61	1146	6.13	0.34	0.04	8.03	0.12
WE	0.52	584	5.20	0.52	0.08	6.13	0.11
WE	0.48	1006	4.80	0.09	0.01	6.62	0.01
WE	0.64	999	6.40	0.15	0.03	5.57	0.02
WE	0.85	1930	8.53	0.14	0.02	7.33	0.01
HB	4.54	4259	45.38	0.19	0.02	7.93	0.00
HB	4.28	3696	42.75	0.18	0.04	4.35	0.00
HB	5.36	4917	53.63	0.25	0.05	5.29	0.00
HB	0.00	0	0.00	0.56	0.15	3.64	na
HB	3.44	3548	34.35	0.23	0.05	4.47	0.00
HB	1.10	1701	10.95	0.11	0.02	4.71	0.01
HB	0.55	1306	5.53	0.07	0.01	4.45	0.01
HB	6.13	4609	61.28	0.16	0.03	4.85	0.00
HB	4.91	5166	49.13	0.15	0.03	4.70	0.00

Table H-2 (continued)

Site	% Tot Carbon	Total Areal Carbon g C m ⁻²	Total Carbon g C kg ⁻¹	MB.C g kg ⁻¹	MB.N g kg ⁻¹	C:N	MBC Quotient
HB	1.14	2270	11.35	0.59	0.10	5.71	0.05
HB	8.89	2860	88.88	0.00	0.00		na
HB	1.14	1999	11.35	0.14	0.03	5.25	0.01
HB	0.00	0	0.00	0.29	0.04	7.98	na
HB	5.14	1519	51.38	0.17	0.03	5.39	0.00
HB	7.43	584	74.25	0.22	0.02	8.94	0.00
HB	7.98	2838	79.83	0.00	0.00		na
HB	0.00	0	0.00	0.00	0.00		na
HB	0.97	1703	9.73	0.42	0.06	7.13	0.03
MD		2417	20.98	0.42	0.06	6.45	0.02
MD		4130	75.43	na	na		na
MD		1340	11.28	0.08	0.02	4.86	0.01
MD		5473	35.95	na	na		na
MD		5966	188.78	na	na		na
MD		2784	22.90	0.17	0.03	5.46	0.01
MD		3702	337.08	na	na		na
MD		3622	44.63	na	na		na
MD		1177	11.88	0.18	0.03	6.50	0.01
UM		2321	12.60	0.26	0.05	5.60	0.02
UM		6030	32.70	na	na		na
UM		4631	21.20	0.37	0.08	4.66	0.02
UM		4602	21.85	0.28	0.06	4.54	0.01
UM		4018	19.73	0.12	0.02	7.18	0.01
UM		3559	17.68	0.36	0.08	4.74	0.02
UM		4697	20.45	na	na		na
UM		4250	19.45	0.14	0.02	6.96	0.01
UM		3307	14.45	0.29	0.06	4.76	0.02

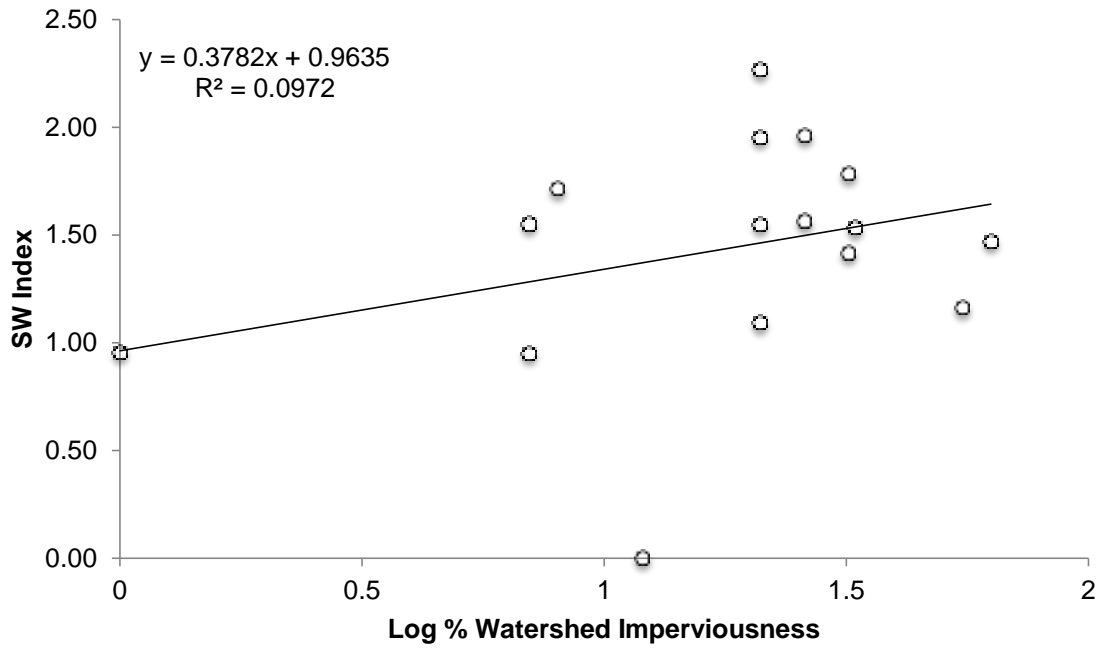


Figure H-1 Watershed imperviousness compared to Shannon-Weiner diversity index in RSCs

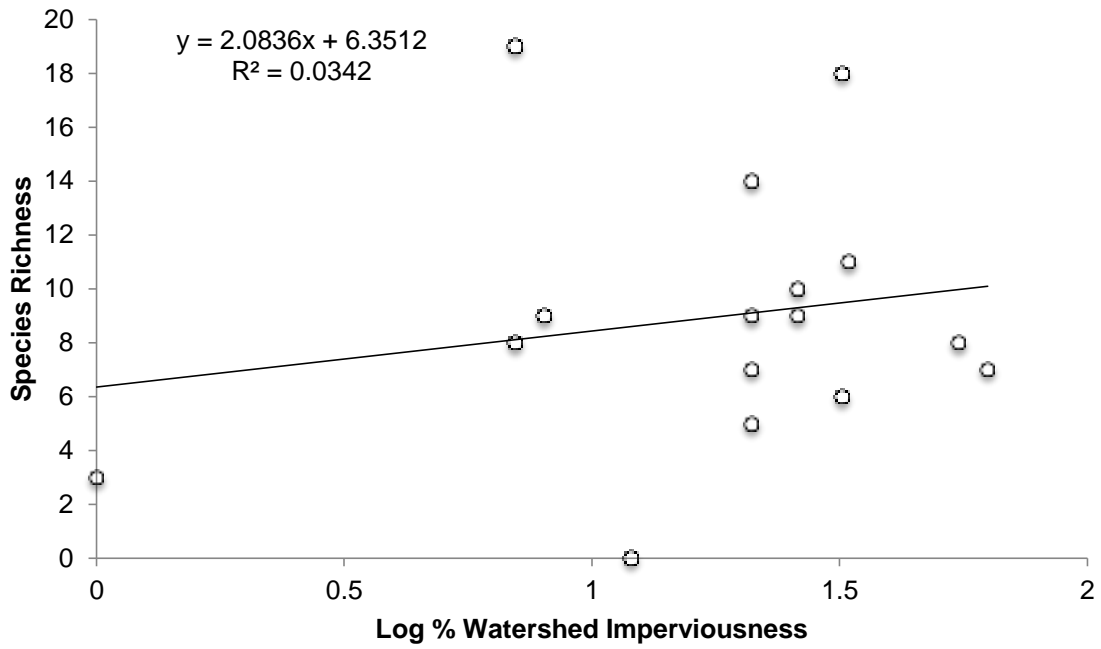


Figure H-2 Watershed imperviousness compared to species richness in RSCs

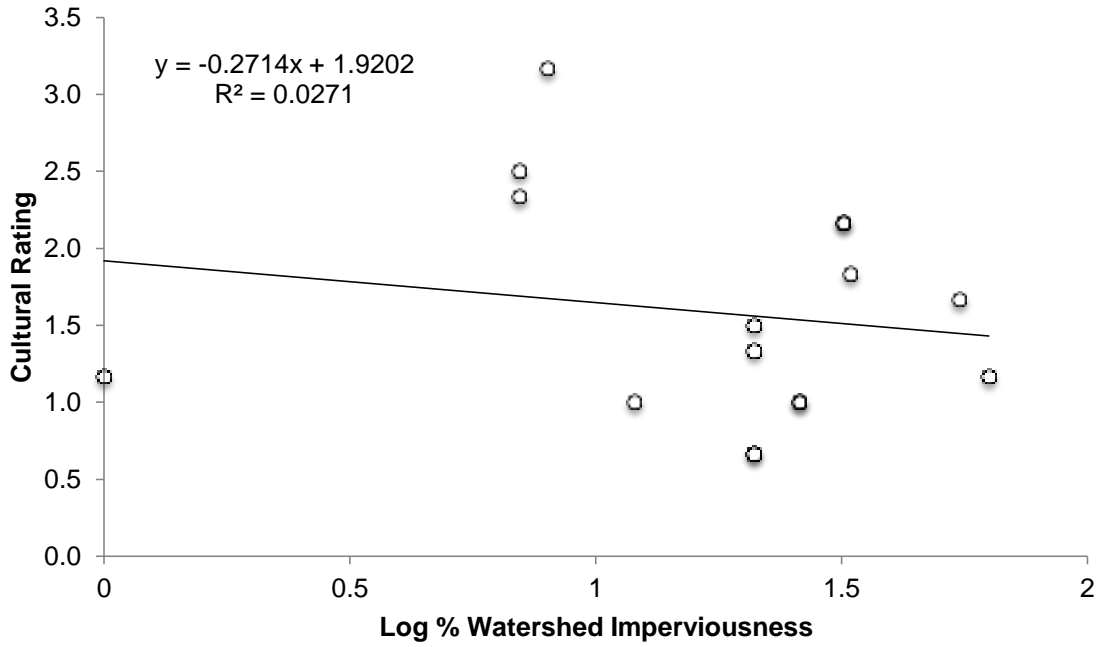


Figure H-3 Watershed imperviousness compared to cultural rating in RSCs

I. Appendix: R-code for Ecosystem Service Analysis

```
### Create subsets
sum.es.1.3 = subset(SumSite, Age<=3)
sum.es.10ref = subset(SumSite, Age>=10)
sum.es.10p = subset(sum.es.10ref, Age<50)
sum.es.ref = subset(SumSite, Age>=50)
sum.es.4p = subset(SumSite, Age>3)
sum.es.4.9 = subset(sum.es.4p, Age<10)

sum.es.wet = subset(SumSite, Wet==1)
sum.es.dry = subset(SumSite, Wet==0)

CN.1.3 = subset(CnNSum, Age<=3)
CN.10ref = subset(CnNSum, Age>=10)
CN.10p = subset(CN.10ref, Age<50)
CN.ref = subset(CN.10ref, Age>=50)
CN.4p = subset(CnNSum, Age>3)
CN.4.9 = subset(CN.4p, Age<10)

CN.wet = subset(CnNSum, Wet==1)
CN.dry = subset(CnNSum, Wet==0)

### Analysis for Age Bins
# Age 1 to 3 vs. 4 to 9
wilcox.test(sum.es.1.3$SWIndex, sum.es.4.9$SWIndex, Paired=FALSE)
> p = 0.9307
wilcox.test(sum.es.1.3$Richness, sum.es.4.9$Richness, Paired=FALSE)
> p = 0.7138
t.test(CN.1.3$IgC0, CN.4.9$IgC0, Paired=FALSE)
> p = 0.1062
t.test(CN.1.3$IgC5, CN.4.9$IgC5, Paired=FALSE)
> p = 0.1392
t.test(CN.1.3$IgTot, CN.4.9$IgTot, Paired=FALSE)
> p = 0.1169
wilcox.test(CN.1.3$MB.C, CN.4.9$MB.C, Paired=FALSE)
> p = 0.0305
wilcox.test(CN.1.3$MB.N, CN.4.9$MB.N, Paired=FALSE)
> p = 0.0039
wilcox.test(sum.es.1.3$Habitat, sum.es.4.9$Habitat, Paired=FALSE)
> p = 0.0559
wilcox.test(sum.es.1.3$Cultural, sum.es.4.9$Cultural, Paired=FALSE)
> p = 0.8696

# Age 1 to 3 vs. 10+
wilcox.test(sum.es.1.3$SWIndex, sum.es.10p$SWIndex, Paired=FALSE)
> p = 0.4286
```



```

wilcox.test(sum.es.1.3$Richness, sum.es.10p$Richness, Paired=FALSE)
> p = 0.7358
t.test(CN.1.3$IgC0, CN.10p$IgC0, Paired=FALSE)
> p = 0.0013
t.test(CN.1.3$IgC5, CN.10p$IgC5, Paired=FALSE)
> p = 0.8671
t.test(CN.1.3$IgTot, CN.10p$IgTot, Paired=FALSE)
> p = 0.0028
wilcox.test(CN.1.3$MB.C, CN.10p$MB.C, Paired=FALSE)
> p = 0.0129
wilcox.test(CN.1.3$MB.N, CN.10p$MB.N, Paired=FALSE)
> p = 0.1122
wilcox.test(sum.es.1.3$Habitat, sum.es.10p$Habitat, Paired=FALSE)
> p = 0.0519
wilcox.test(sum.es.1.3$Cultural, sum.es.10p$Cultural, Paired=FALSE)
> p = 0.0529

```

```

# Age 1 to 3 vs. ref
wilcox.test(sum.es.1.3$SWIndex, sum.es.ref$SWIndex, Paired=FALSE)
> p = 0.6429
wilcox.test(sum.es.1.3$Richness, sum.es.ref$Richness, Paired=FALSE)
> p = 0.3932
t.test(CN.1.3$IgC0, CN.ref$IgC0, Paired=FALSE)
> p = 0.0007
t.test(CN.1.3$IgC5, CN.ref$IgC5, Paired=FALSE)
> p = 0.0302
t.test(CN.1.3$IgTot, CN.ref$IgTot, Paired=FALSE)
> p = 0.0012
wilcox.test(CN.1.3$MB.C, CN.ref$MB.C, Paired=FALSE)
> p = 0.0111
wilcox.test(CN.1.3$MB.N, CN.ref$MB.N, Paired=FALSE)
> p = 0.1101
wilcox.test(sum.es.1.3$Habitat, sum.es.ref$Habitat, Paired=FALSE)
> p = 0.0519
wilcox.test(sum.es.1.3$Cultural, sum.es.ref$Cultural, Paired=FALSE)
> p = 0.3696

```

```

# Age 4 to 9 vs. 10p
wilcox.test(sum.es.10p$SWIndex, sum.es.4.9$SWIndex, Paired=FALSE)
> p = 0.4344
wilcox.test(sum.es.10p$Richness, sum.es.4.9$Richness, Paired=FALSE)
> p = 0.381
t.test(CN.10p$IgC0, CN.4.9$IgC0, Paired=FALSE)
> p = 0.0297
t.test(CN.10p$IgC5, CN.4.9$IgC5, Paired=FALSE)
> p = 0.6905
t.test(CN.10p$IgTot, CN.4.9$IgTot, Paired=FALSE)

```

```

> p = 0.0508
wilcox.test(CN.10p$MB.C, CN.4.9$MB.C, Paired=FALSE)
> p = 0.4205
wilcox.test(CN.10p$MB.N, CN.4.9$MB.N, Paired=FALSE)
> p = 0.5706
wilcox.test(sum.es.10p$Habitat, sum.es.4.9$Habitat, Paired=FALSE)
> p = 0.1147
wilcox.test(sum.es.10p$Cultural, sum.es.4.9$Cultural, Paired=FALSE)
> p = 0.0759

# Age 4 to 9 vs. ref
wilcox.test(sum.es.4.9$SWIndex, sum.es.ref$SWIndex, Paired=FALSE)
> p = 0.5714
wilcox.test(sum.es.4.9$Richness, sum.es.ref$Richness, Paired=FALSE)
> p = 0.5714
t.test(CN.ref$IgC0, CN.4.9$IgC0, Paired=FALSE)
> p = 0.0357
t.test(CN.ref$IgC5, CN.4.9$IgC5, Paired=FALSE)
> p = 0.5885
t.test(CN.ref$IgTot, CN.4.9$IgTot, Paired=FALSE)
> p = 0.0429
wilcox.test(CN.4.9$MB.C, CN.ref$MB.C, Paired=FALSE)
> p = 0.3406
wilcox.test(CN.4.9$MB.N, CN.ref$MB.N, Paired=FALSE)
> p = 1
wilcox.test(sum.es.4.9$Habitat, sum.es.ref$Habitat, Paired=FALSE)
> p = 0.1147
wilcox.test(sum.es.4.9$Cultural, sum.es.ref$Cultural, Paired=FALSE)
> p = 0.5541

# Age 10p vs. ref
wilcox.test(sum.es.10p$SWIndex, sum.es.ref$SWIndex, Paired=FALSE)
> p = 0.6667
wilcox.test(sum.es.10p$Richness, sum.es.ref$Richness, Paired=FALSE)
> p = 0.6667
t.test(CN.ref$IgC0, CN.10p$IgC0, Paired=FALSE)
> p = 0.7644
t.test(CN.ref$IgC5, CN.10p$IgC5, Paired=FALSE)
> p = 0.5418
t.test(CN.ref$IgTot, CN.10p$IgTot, Paired=FALSE)
> p = 0.9188
wilcox.test(CN.10p$MB.C, CN.ref$MB.C, Paired=FALSE)
> p = 0.8152
wilcox.test(CN.10p$MB.N, CN.ref$MB.N, Paired=FALSE)
> p = 0.7952
wilcox.test(sum.es.10p$Habitat, sum.es.ref$Habitat, Paired=FALSE)
> p = 1

```

```
wilcox.test(sum.es.10p$Cultural, sum.es.ref$Cultural, Paired=FALSE)
> p = 1

# Wet v. Dry
wilcox.test(sum.es.wet$SWIndex, sum.es.dry$SWIndex, Paired=FALSE)
> p = 0.462
wilcox.test(sum.es.wet$Richness, sum.es.dry$Richness, Paired=FALSE)
> p = 0.2182
t.test(CN.wet$IgC0, CN.dry$IgC0, Paired=FALSE)
> p = 0.301
t.test(CN.wet$IgC5, CN.dry$IgC5, Paired=FALSE)
> p = 0.6415
t.test(CN.wet$IgTot, CN.dry$IgTot, Paired=FALSE)
> p = 0.2568
wilcox.test(CN.wet$MB.C, CN.dry$MB.C, Paired=FALSE)
> p = 0.0221
wilcox.test(CN.wet$MB.N, CN.dry$MB.N, Paired=FALSE)
> p = 0.1133
wilcox.test(sum.es.wet$Habitat, sum.es.dry$Habitat, Paired=FALSE)
> p = 0.0337
wilcox.test(sum.es.wet$Cultural, sum.es.dry$Cultural, Paired=FALSE)
> p = 0.0122
```