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Performance of regenerative stormwater conveyance (RSC) as a nature-based stormwater control measure (SCM)

Performance des systèmes d'adduction d'eau pluviale régénérée (RCS) comme une mesure naturelle de contrôle des eaux pluviales (SCM)

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RÉSUMÉ

« Regenerative Stormwater Conveyance » (RSC - transport régénératif des eaux de pluie) applique les principes de restauration des ruisseaux pour créer un flux éphémère par paliers pour transporter et traiter les eaux de ruissellement, ainsi que pour fournir des services écosystémiques essentiels dans les zones urbaines et suburbaines. Une évaluation rigoureuse du RSC sur le terrain est nécessaire pour bien comprendre la capacité de ces systèmes à gérer les flux d'eaux pluviales, à la fois en termes d'hydrologie et de qualité de l'eau. Un suivi hydrologique et de la qualité de l'eau sur deux sites situés en Caroline du Nord (NC), l'un dans la plaine côtière et l'autre dans les écorégions du piedmont, ont débuté à l'automne 2012. Les données montrent que le RSC atténue efficacement les eaux de ruissellement en termes de volume et de débit maximum. En outre, les autres fonctions des écosystèmes, dont la séquestration du carbone, la biodiversité, la formation des sols, le potentiel de l'habitat et le cycle des nutriments, sont quantifiés par une enquête de terrain sur des sites en Caroline du Nord et dans le Maryland. Dans l'ensemble, les systèmes RSC semblent offrir une alternative intéressante de gestion des eaux pluviales et pour les eaux de ruissellement dans les zones urbaines et suburbaines.

ABSTRACT

Regenerative stormwater conveyance (RSC) uses principles from stream restoration to create a step-pool ephemeral stream to convey and treat stormwater runoff, as well as provide critical ecosystem services in urban and suburban areas. Rigorous field evaluation of RSC is necessary to truly understand the ability of such systems to manage stormwater flows, both in terms of hydrology and water quality. Hydrologic and water quality monitoring of two RSC sites located in NC, one in the Coastal Plain and one in the Piedmont eco-regions commenced in Fall 2012. Data show that RSC effectively mitigate stormwater runoff in terms of volume and peak flow reduction. Additionally, other ecosystem functions, including carbon sequestration, biodiversity, soil formation, habitat potential, and nutrient cycling, are quantified via a field survey of sites in NC and MD. Overall, RSC systems appear to be an attractive stormwater management alternative to manage stormwater runoff in urban and suburban areas.

KEYWORDS

Ecosystem services, Regenerative stormwater conveyance, Stormwater control measures

1 INTRODUCTION

Natural ecosystems are indispensable to the wellbeing of humanity: providing food and water, climate regulation, recreation, and more (MEA, 2005). However, many of native ecosystems are being lost or compromised by urbanization and suburbanization. Urban influenced degradation of ecosystems can be attributed, in part, to nonpoint pollution sources such as stormwater runoff (Beale and Sheldon, 2003). Land is converted from pervious surfaces, which absorb water during a rain event, to impervious surfaces, which are unable to absorb water, resulting in large volumes of water and associated pollutants entering nearby streams. Stormwater pollution is associated with higher peak discharges, increased frequency and severity of flooding, greater water export from the watershed, reduced in-stream nutrient removal, and diminished groundwater levels (Klein, 1979; Grimm et al., 2000; Delleur, 2003; Galloway et al., 2004). Although, urban areas are required to manage stormwater, many conventional storm drainage networks merely route stormwater from the developed area directly to the stream channel, which may only exasperate the aforementioned problems (Walsh et al., 2005).

A new paradigm in approaching urban hydrology includes not only protecting and maintaining the safety and health of communities and the natural environment, but doing so sustainably (Delleur, 2003). Sustainability, in this case, involves creating water systems which fully contribute to the objective of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity (UNESCO). An emerging sustainable approach to stormwater management is regenerative stormwater conveyance (RSC) (Underwood et al., 2005; Baldwin, 2005; Bukaveckas, 2007; Browning, 2008; Filoso and Palmer, 2009). RSCs are open channel, sand seepage filtering systems that utilize a series of shallow aquatic pools, riffle weir grade controls, native vegetation, and underlying sand channels to treat, safely attenuate, and convey storm flow. Additionally, RSC systems convert stormwater to ground water through infiltration and below ground seepage (Brown, 2009). These systems are designed to restore aspects of ecosystem function which treat and mitigate inflow, and may, in fact, offer additional ecosystem function beyond that of conventional stormwater control measures (SCMs, a.k.a best management practices, BMPs).

Currently, information regarding RSC performance is primarily observational. Grab sample research in Anne Arundel County, Maryland (MD), shows nitrogen reduction similar to that of other SCMs (Brown, 2009; Filoso and Palmer, 2009; Browning, 2008; Underwood et al., 2005; Flores et al., 2009). Pre-installation modeling of another RSC system in MD estimated a discharge volume four times less than that of existing conditions for a 25-year storm event (Brown, 2009). Further research is needed to evaluate the ability of RSCs to facilitate infiltration and peak volume mitigation, especially in different soil types. Additional ecosystem function observed within RSC systems include biodiversity, carbon sequestration, and aesthetics (Underwood et al., 2005; Browning, 2008; Flores et al., 2009); however, understanding of the extent of the services offered by RSC requires more thorough quantitative evaluation. RSC systems have also been shown to require less capital investment and maintenance costs than conventional BMPs (Brown, 2009). Therefore, RSC systems appear to be a very attractive stormwater management alternative to manage stormwater runoff in urban and suburban areas.

This work intends to

- i. Determine the effectiveness of RSC at achieving typical stormwater water quality criteria, in particular system removal of N and P during a storm event;
- ii. Determine RSC hydraulic performance in different soil types by quantifying system hydrology;
- iii. Quantify additional ecosystem services provided by RSC, including carbon sequestration, biodiversity, nutrient processing, and habitat potential;

The results of this work will provide insight on the ability of RSC systems to provide stormwater management, as well as additional ecosystem function in urban and suburban areas. It is anticipated that RSC systems offer an effective and beneficial alternative to stormwater management in urban and suburban areas.

1. METHODS

Research is being conducted on two newly constructed RSC systems in NC. Sites will undergo evaluation of hydrology and water quality for a minimum of 12 months. Ecosystem service assessment will take place at several existing RSC systems in MD and nearby reference sites, in addition to the NC sites. Ecosystem assessment includes measurements of carbon sequestration, biodiversity, nutrient cycling, soil formation, and habitat provision.

1.1 Site Descriptions

RSC sites in NC are to be researched extensively, with one site in the Coastal Plain and one site in the Piedmont. The regions have significantly different soil types, as the coastal plain is composed of sandy or loamy sand (Soil Hydraulic Group A/B) and the Piedmont is composed primarily of clay (Soil Hydraulic Group C/D). This will allow for comparative evaluation between regions on the ability of RSC systems to function as SCMs. Several existing and established sites in Anne Arundel County, MD will be evaluated during the summer of 2012 and 2013 for additional ecosystem benefits.

1.1.1 Brunswick County

The Coastal Plain eco-region site consist of a retrofit RSC system along Hwy 17 Royal Oak Bridge over Lockwood Folly near Supply, NC. The watershed is 12.5 acres consisting of 1 ac NC DOT impervious area (i.e. Hwy 17). The site is dominated by Baymeade/Marvyn and Muckalee loam soils, which fall into Soil Hydraulic Group A. The 3-pool RSC, completed in July 2012, has an overall slope of 4% (Figure 1a).



(a)



(b)

Figure 1. RSCs in (a) Brunswick Co, NC after construction, and (b) MD, 8 years old. Photos by A. Cizek.

1.1.2 Alamance County

An RSC site is under construction in Alamance County (Piedmont eco-region of NC). The system will capture stormwater runoff from a 3 ac. Rest Area off of I-85/I-40. The site is composed primarily of Wilkes soil series with 6 inches of sandy loam covering 6 to 8 inches of tight clay ($K_{sat} = 0$ to 0.01 in/hr). The RSC will have an overall slope of 5%.

1.1.3 Maryland Sites

Sites in Maryland consist of 5 RSCs located around Anne Arundel County aged between 2 and 12 years. The sites vary in both slope and location (urban, suburban, etc.). An example of the 8-yr-old site is shown in Figure 1b.

1.2 Stormwater Mitigation Performance

The ability of RSC systems to function as stormwater control measures is determined by the ability of such systems to reduce pollutant loadings and re-establish pre-development hydrology. Hydraulic and water quality measurements are taken for storm events over the course 12 months. Monitoring weirs are placed at the inlet and outlet of each pool within the system to measure surface flow. Additionally, RSC systems promote groundwater infiltration, thus a monitoring well and piezometer are located within the center of each pool.

1.2.1 Hydraulic Mitigation

Once water enters an RSC system, it can exit as surface flow, groundwater seepage, evapotranspiration, and infiltration. Hobo pressure transducers (Brunswick Co.) and ISCO bubbler modules (Alamance Co.) collect 2-min interval water depth measurements at the inlet and outlet monitoring weirs of the step-pools. Peak flow reduction and overall volume reduction of each pool, as

well as the overall RSC system are calculated from these flow measurements. In addition, the system inlet and outlet flow is used to determine the pre- and post-SCM hydrographs for each storm. An infiltration ditch is located beneath each pool to allow for subsurface stage measurements. Sampling wells are used to measure the infiltration within the infiltration ditch. Infiltration rates are back calculated over the entire storm event based on the measured stage change and area calculations (Figure 2).

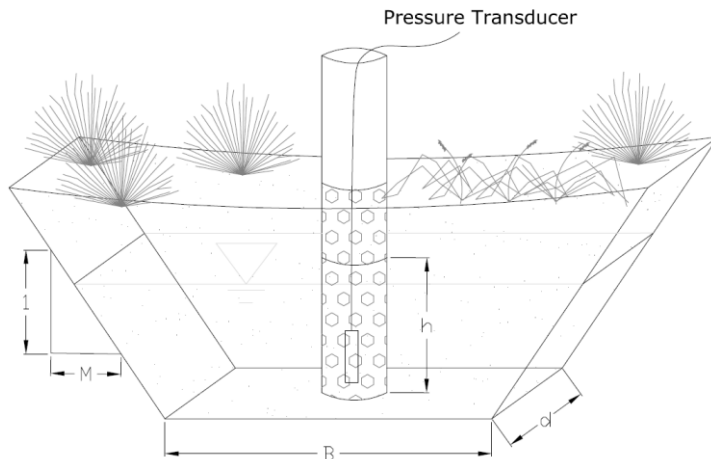


Figure 2. Section of RSC media bed including the sampling well used to measure seep off.

Evapotranspiration (ET) is calculated using reference daily ET values measured at KSUT-Brunswick Co Airport in Southport, NC for the Brunswick site and KBUY-Burlington Alamance Airport for the Alamance site. The Penman-Monteith equation is used to determine the ET for the specific vegetation present at the RCS site. Each pool is connected by media. Therefore, movement in and out of a pool can be via flow through the media. Subsurface flow out from each pool is estimated using the water balance, such that

$$Q_{media,out} = Q_{surface,in} + Q_{precip} + Q_{media,in} - Q_{surface,out} - Q_{infiltr} - Q_{ET}$$

The aforementioned measurements should account for all of the water within the system. The system water balance aids in visualizing the pathway of water through an RSC system.

1.2.2 Water Quality Mitigation

Water quality samples are taken at the Alamance site only. ISCO 6712 automated samplers collect flow-weighted composite samples at each sampling point to determine event mean concentrations (EMCs) over the course of a storm event. EMCs are measured for Total Suspended Solids (TSS), Total Phosphorus (TP), and Nitrogen (including total nitrogen (TN), Nitrite-Nitrogen (NO₂-N), Nitrate-Nitrogen (NO₃-N), and Ammonium-Nitrogen (NH₄-N)). Additionally, pH and temperature are measured for each sample. The total loading of pollutants exiting the system is more descriptive of RSC performance, as it depends on the flow and pollutant concentration exiting the system. The overall pollutant loading is calculated for each contaminant measured in field by multiplying the total volume of runoff by the EMC. Water quality sampling will commence in February 2013.

1.3 Additional Ecosystem Service Measurements

An advantage of a nature-based SCM design is that in addition to the designed stormwater mitigation services, the systems may offer additional services generally attributed to healthy ecosystems. It is expected that RSC will offer some degree of opportunity for carbon sequestration, biodiversity, nutrient cycling, soil formation, and habitat provision. It is the intent of this research to measure the extent of these services offered in comparison with their previous eroded conditions, as well as natural reference conditions (pre-development). Ecosystems are assessed during the summer months at all sites. Additional ecosystem assessment occurs at the Alamance site during each of the other seasons (fall, winter, and spring) to establish a picture of the seasonal development of said functions.

1.3.1 Carbon Sequestration

As with natural streams/floodplains, RSC systems have elaborate designs which incorporate both (semi) continuous flow stream zones to convey water through the system, as well as disconnected

“seepage wetlands” where important processes occur. Carbon sequestration by RSC systems is evaluated based on carbon measurements taken over time at the chronosequence of sites and presented as a carbon sequestration rate. At each site, a series of three transects is established from the inlet to the outlet, thus spanning the length of the system. The transects are established such that it incorporates the “flood plain” and pool. Along each transect, three soil cores are collected from the upper 20 cm of the soil profile. Soil cores for bulk density determination are concomitantly collected in order to express organic carbon content on an areal basis.

1.3.2 Nutrient Cycling

Soil microbial biomass will be measured as an indicator of microbial activity. Soil cores (4-in deep) are taken at three points across the three carbon transects. Samples undergo the fumigation-extraction procedure, as described by Rice *et al.* (1996). These results are compared to sampled reference sites and other comparable sites in the literature (Sparling, 1997).

1.3.3 Biodiversity

Biodiversity is an indicator of the health of an ecosystem (Zedler, 2000), and has been linked to other important ecosystem services such as pest control (Hunt *et al.*, 2006) and education and recreation potential (MEA, 2005). Vegetation biodiversity is determined by randomly placing a 0.5-m² quadrat in the vicinity of the carbon assessment transects. All vegetation growing within the quadrat is identified and enumerated. Species richness and evenness will be calculated using the Shannon-Weiner diversity index (Dodds, 2002).

1.1.1 2.3.4 Soil Formation

Earthworms, essential for soil formation, will be counted by a combination of handsorting and the formalin expulsion technique. One 10-in by 10-in by 10-in soil sample is taken at each carbon transect. The soil is handsorted and earthworms removed. Formalin is applied to the bottom of the sample hole and any additional earthworms expelled are collected (Blair *et al.*, 1996).

1.3.4 Habitat Provision

Many urban areas have destroyed natural habitats, which are important for different species survival. Underwood *et al.* (2005) documented the provision of the Atlantic White Cedar using a step-pool conveyance design. In order to determine RSC ability at habitat provision, habitat services provided by each of the sites are assessed using an adapted rubric developed for North Carolina wetlands. Habitat indicators, including vegetation structure, food value of vegetation for wildlife, and other direct observations of wildlife (i.e. nests, tracks, scat, etc.) are used to assign the site a score of 0 to 4.

2. RESULTS

2.1 Hydraulic Performance

Surface flow monitoring at Brunswick Co began in August 2012 and subsurface in October 2012. Of the nine storms with measurable inflow, only three have produced surface outflow from the system, resulting in a cumulative volume reduction of 85%. One outflow producing storm event (max precipitation intensity = 0.7 in/hr, total precipitation = 1.2 in) saw a 95% reduction in peak flow and an 87% reduction in runoff volume entering Lockwood Folly (Figure 3).

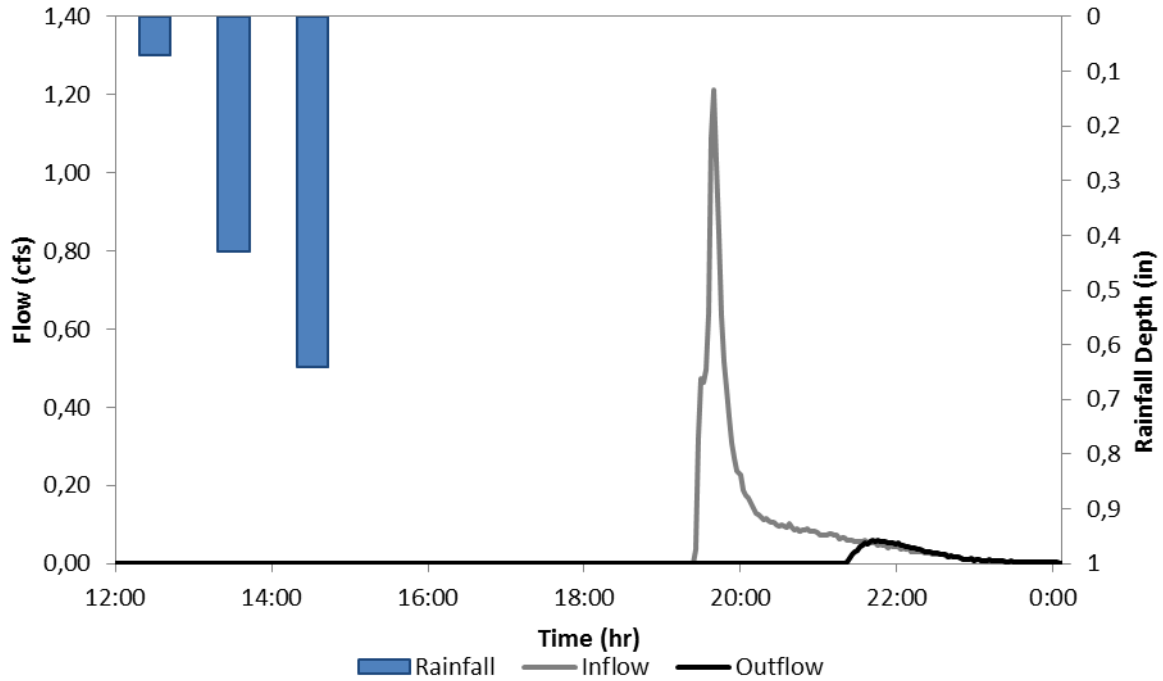


Figure 3. Inflow and outflow hydrograph from 10-8-12 storm event recorded at Brunswick Co RSC.

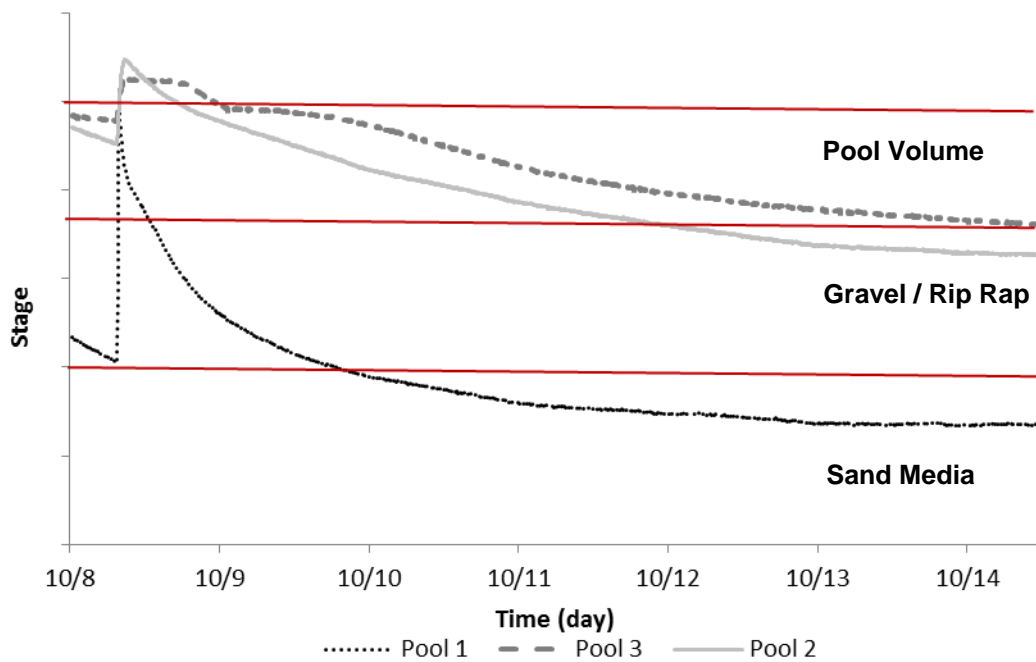


Figure 4. Stage heights within each pool at Brunswick Co RSC during the 10/8/12 storm event.

Interestingly, pool 1 has yet to release surface flow into pool 2, but pool 2 receives a significant amount of water via subsurface seepage. Surface flow has been recorded on several occasions between pool 2 and pool 3. Stage measurements from the monitoring wells show water level in pool 1 ponding up to the exit weir height at the onset of the storm event, and then a relatively rapid release of water via subsurface seepage, and, to a lesser degree, infiltration (average rate calculated as 0.08 in/hr) (Figure 4). Pools 2 and 3 similarly pond water, release some via treated surface runoff, and release water more slowly, suggesting that infiltration may play a slightly larger role in these pools than in pool 1.

As of October, 2012, RSC system performance shows that the predominant pathway of release is subsurface seepage (Figure 5). As monitoring continues throughout the vegetative establishment of the system, ET is likely to play a more important role in the water balance. The measured infiltration rates within the infiltration trenches is much lower than initially expected, possibly due to a change in soil texture from sand to silt at the system depth or to compaction during construction. Despite the reason, infiltration serves a unexpectedly small role in the overall water balance. Ultimately, the water balance reveals that since much of the runoff is exiting the system as subsurface seepage, it is being released having undergone a high degree of treatment (i.e. media filtration).

2.2 Water Quality Mitigation Performance

Water quality will be measured at the Alamance Co RSC site beginning in February 2013. Based on the hydrology recorded at the Brunswick Co site (described in the Section 3.1), pollutant reductions are expected to be similar to that of bioretention with internal water storage (IWS) (Hunt et al., 2012), namely up to 60% reduction for TN and TP.

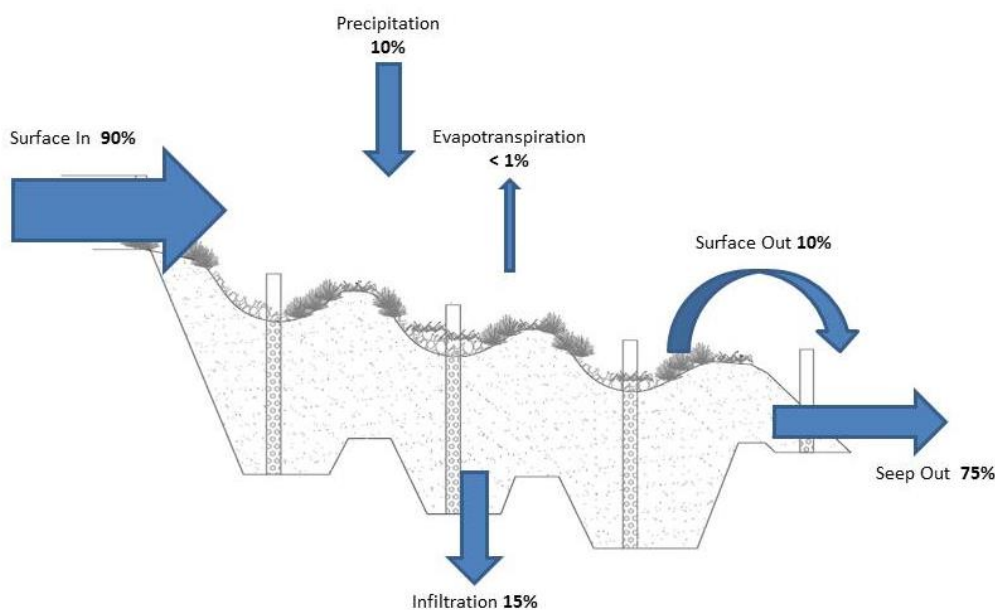


Figure 5. Cumulative system water balance of monitored storms since October 2012

2.3 Additional Ecosystem Function

Ecosystem function often takes time to and may never resemble function offered by undisturbed ecosystems (Craft *et al.*, 2003). Therefore, ecosystem analysis incorporates evaluation of RSC systems in NC and MD ranging in age between two and twelve years. Of the ecosystem metrics examined at the Maryland sites, data has been processed for plant diversity, earthworm counts, and habitat provision (Figure 6). The remaining data is expected to be processed by December 2012. Measurements are presented relative to the age of the system.

In terms of plant diversity, all the RSCs examined displayed Shannon-Weiner indices between 1.6 and 2.3 independent of system age, similar to that of the reference site (Figure 6a). The two systems with the lowest indices (6-yr and 12-yr old sites) are unique habitats dominated by Atlantic White Cedars. Although these habitats serve a niche role (Underwood *et al.*, 2006), they are not ranked high in terms of biodiversity. This may be a limit of plant biodiversity as a metric for overall ecosystem health.

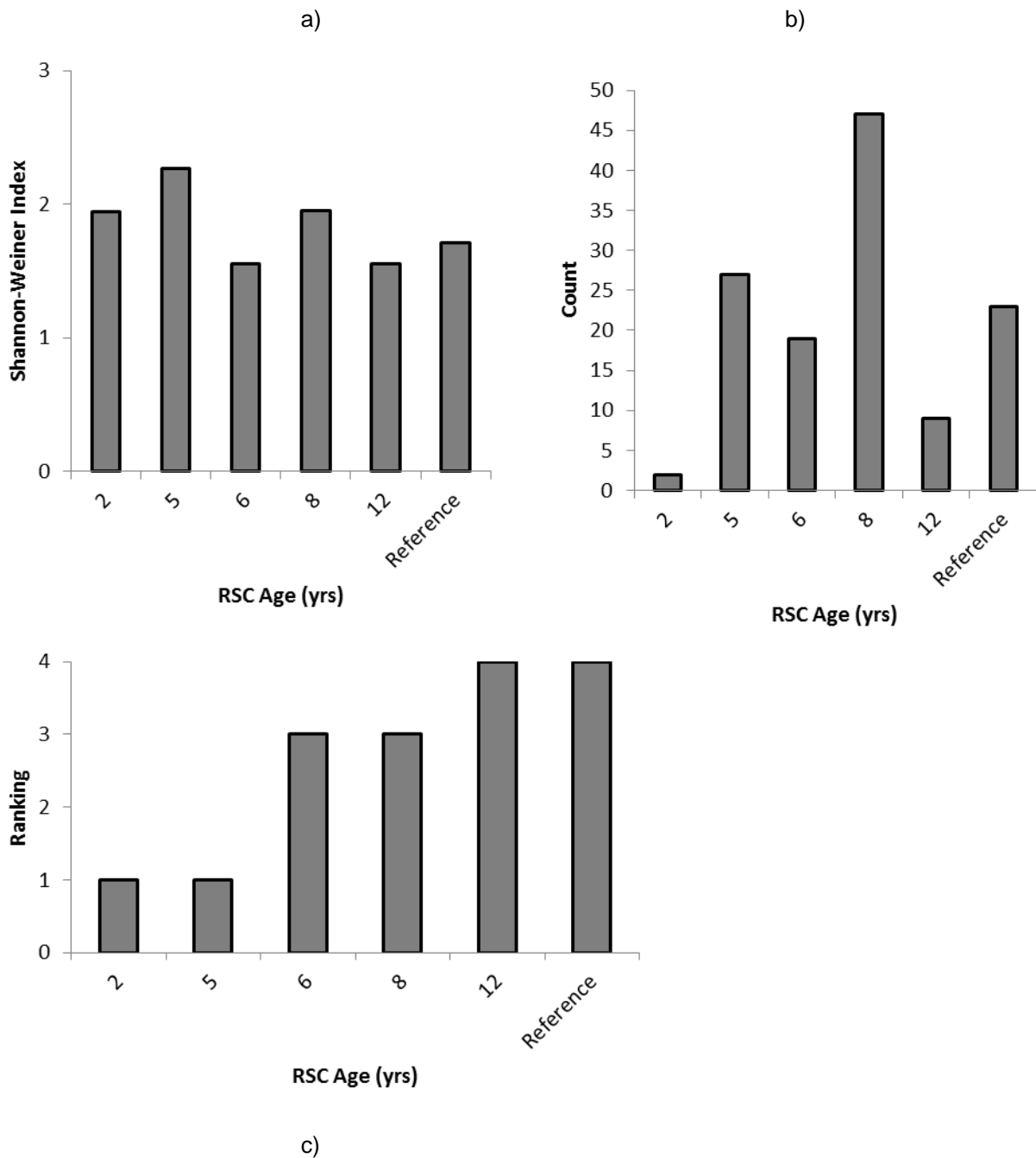


Figure 6. Results from ecosystem assessment on RSC sites in Maryland during May 2012, metrics include (a) plant biodiversity, (b) earthworm counts, and (c) habitat provision.

Earthworm counts also do not show an apparent increasing trend with age (Figure 6b). The sites hosting the Atlantic White Cedars tend to be much wetter than the other sites, with permanent water as opposed to ephemeral or intermittent flow. Such systems are not characteristically good habitat for earthworms. If we eliminate these sites (6-yr and 12-yr old sites), there is an increasing count with age. Soil at the 2-year old site was observed as compacted, clayey, with only early vegetation. Soil at the 8-yr old site was much more organic and loose, more consistent with earthworm habitat (Blair et al., 1996).

Habitat ranking shows a very clear establishment with age (Figure 6c), likely attributed to the time needed to establish food bearing vegetation, such as trees and shrubs. The function of habitat provision is also less dependent than other metrics examined on the type of ecosystem (i.e. permanently wet vs. intermittently wet), and more dependent on broader aspects of an ecosystem (i.e. food, shelter, etc.). The additional services examined (microbial biomass and carbon sequestration) are also less dependent on type of system and will likely show characteristic of establishment over

time.

3. DISCUSSION

Based on the data collected on the Brunswick system, RSC likely provides effective stormwater hydrologic mitigation, in that there is no surface outflow for rainfall events < 1 in (the one exception to this was 8 hours preceded by a large storm event), and peak flow and overall volume reductions are highly reduced. It is expected that water quality analysis will show similar mitigation effectiveness. Furthermore, RSC systems exhibit, over time, additional ecosystem services similar to those observed at reference sites. Although the evaluation process is set up to be as objective as possible, variability has been observed using ecosystem measurements that favor a particular type of system, which may not give clear results of ecosystem health. This requires thorough observation and note taking while on site. Further data processing and additional sampling will likely reveal more clear patterns on this front.

4. CONCLUSIONS

RSC systems offer a potential cost effective, attractive, and sustainable approach to urban and suburban water system planning by restoring/creating ecosystems that provide stormwater management services, as well as additional services such as carbon sequestration and biodiversity. The anticipated contributions of this research will be four-fold. First, RSC systems are relatively new in their use, there is very limited hard data regarding the performance of said systems as stormwater SCMs (Underwood *et al.*, 2005; Browning, 2008). This work contributes and expands upon current research by evaluating multiple sites and using collected data to eventually project performance over a variety of storm sizes. Second, current data published regarding RSC systems ability to regenerate ecosystems is limited to qualitative observations (Underwood *et al.*, 2005; Browning, 2008). This work provides quantitative data in regards to the potential for RSC systems to exhibit biodiversity, soil formation, nutrient processing and habitat potential. Third, studies show disparate results as to the ability of restored or created ecosystems to provide services comparable to that of natural ecosystems (Craft *et al.*, 2003; Clewell, 1999). This work contributes further to this arena by comparing ecosystem services present in RSC system to those present at natural reference sites. It is the hope of this work that the valuation of other SCMs will be based on stormwater mitigation effectiveness, as well as ecosystem function. Ultimately, this research provides a more accurate means to determine the appropriate stormwater approach to a given situation.

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