

Assessment of a rainwater harvesting system for pollutant mitigation at a commercial location in Raleigh, NC, USA

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ABSTRACT

Low Impact Development (LID) and Water Sensitive Urban Design have as one of their tenets the use of rainwater harvesting (RWH) systems to provide water for use on site. Historically implemented in arid or semi-arid regions, RWH has recently surged in popularity in more humid regions, such as the southeastern USA, due to increased interest in water conservation during severe drought conditions. An LID commercial site in Raleigh, NC, incorporated RWH with other stormwater control measures to mitigate runoff quantity and improve runoff quality. A 57,900-liter RWH tank used for landscape irrigation was monitored to determine influent and effluent water quality. Samples were analyzed for total nitrogen, total phosphorus, total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrite-nitrate (NO_x), orthophosphate (Ortho-P) and total suspended solids (TSS). Low concentrations were observed for all pollutants monitored; for example, influent and effluent TP concentrations were 0.02 and 0.03 mg/L, respectively. Statistical testing showed significant increases in TAN and organic nitrogen (ON) concentrations by 33 and 38%, respectively, from inflow to outflow. NO_x and TSS concentrations decreased significantly by 23 and 55%, respectively. Concentrations of all other pollutants were not significantly different between the inflow and outflow. Influent concentrations to the RWH tank were less than previously published rainfall pollutant concentrations, indicating potentially irreducible concentrations onsite. While a single case study, this RWH system appears to offer some pollutant mitigation, especially for TSS.

Key words | irrigation, Low Impact Development, North Carolina, nutrient management, rainwater harvesting, stormwater management

INTRODUCTION

Low Impact Development (LID; [Prince George's County 1999](#)), describes an approach to stormwater management, which focuses on minimizing stormwater impacts onsite and mimicking predevelopment hydrology. Related terminology worldwide includes Water Sensitive Urban Design and Sustainable Urban Drainage Systems. Restoring the predevelopment hydrology of a site places a focus on increasing evapotranspiration and infiltration, decreasing runoff volumes and peak flows and addressing water capture and use onsite ([Coffman 2000](#)). LID also emphasizes water capture and use onsite by employing rainwater harvesting (RWH) systems.

The most cost-effective use for RWH systems is to provide an alternative water source for non-potable needs such as irrigation, toilet flushing, car washing and laundry. Up to a 70% reduction in the demand for potable water can be expected for an LID incorporating RWH systems versus a conventional development ([van Roon 2007](#)). This, however, is dependent on consistent, year-round use(s) for the harvested water to minimize tank overflow ([Jones & Hunt 2010](#)).

Historically implemented in arid or semi-arid regions, RWH has recently surged in popularity in more humid

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regions, such as the southeastern USA, due to increased interest in water conservation, severe drought conditions, restrictions on lawn irrigation, and economic incentives (Jones & Hunt, 2010; DeBusk *et al.* 2014). If a RWH system is designed and used properly, some authorities (e.g. NCDENR 2009) give runoff mitigation credit.

Rooftop runoff captured by RWH systems contains pollutants such as metals, organics, sediment, and microbiological contaminants, which are deposited through dustfall and atmospheric deposition (Abbasi & Abbasi 2011). Though no regulatory credit is given to RWH for nutrient removal in North Carolina (NC), observed reductions in total nitrogen (TN; 81%) and total phosphorus (TP; 90%), as well as total suspended solids (TSS; 97%) loads have been modeled due to the sedimentation potential of RWH systems (Khastagir & Jayasuriya 2010). Though TSS reduction was not observed, DeBusk & Hunt (2014) observed concentration reductions for nitrogen (45–62%) and phosphorus (15%) species. RWH not only provides for a safe and supplemental water supply, but it also has the potential for mitigation of sediment-bound pollutants.

A RWH system was installed as a component of a commercial LID system in Raleigh, NC. The focus was on nutrient and sediment mitigation, as these are pollutants of concern in North Carolina. The objectives of this study were to (1) assess the pollutant mitigation of this RWH

system, (2) discuss pollutant removal mechanisms employed by RWH systems, and (3) compare the system performance to that of other RWH systems.

METHODS

A RWH component of a LID commercial site in Raleigh, NC, was monitored from January 2012 to December 2012 for runoff quality. Located in the piedmont region, Raleigh, the capital of NC, has a population of approximately 400,000 (US Census Bureau 2013). Normal average monthly temperatures range from 4.2 °C in January to 25.9 °C in August (SCO 2012). The 30-year average precipitation for Raleigh, NC is 1,179 mm/year (NOAA 2006; SCO 2012).

Site description

The 2.5-ha commercial LID site, consisting of a mix of businesses and restaurants, an asphalt parking lot, vegetated parking islands, and a preserved natural wooded area, drained into a series of aboveground and underground stormwater control measures (SCMs), including three RWH tanks (Figure 1). The drainage area and land use characteristics of the site are found in Table 1.

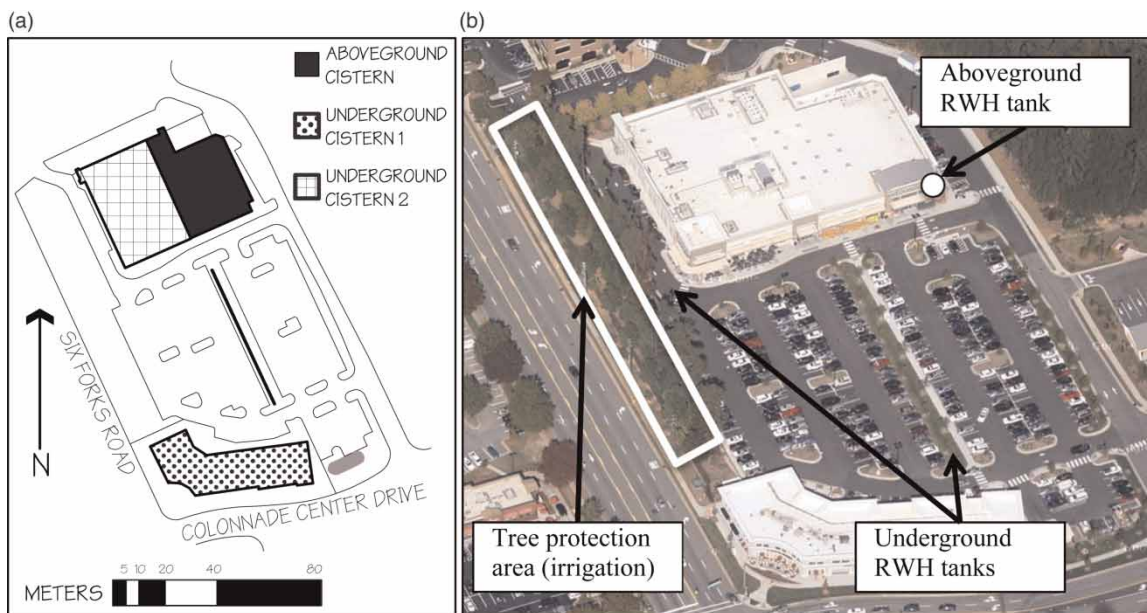


Figure 1 | From left: (a) drainage area of each RWH tank and (b) location of RWH tanks onsite.

Table 1 | Site characteristics

Location	Intersection of Six Forks Road & Colonnade Center Drive, Raleigh, NC (35.900°N, -78.651°W)
Year built	2011
Watershed	Neuse River Basin
Land uses	Commercial businesses, grocery store, and restaurant

Three RWH tanks, totaling 162,800 L of storage, captured runoff from the rooftops and utilized the water onsite for indoor and outdoor needs (Figure 2). One in particular, a 57,900-liter underground tank, hereafter referred to as Underground Tank 1 (UT1, Figure 2) captured runoff from the northern rooftop (2,100 m² surface area). The

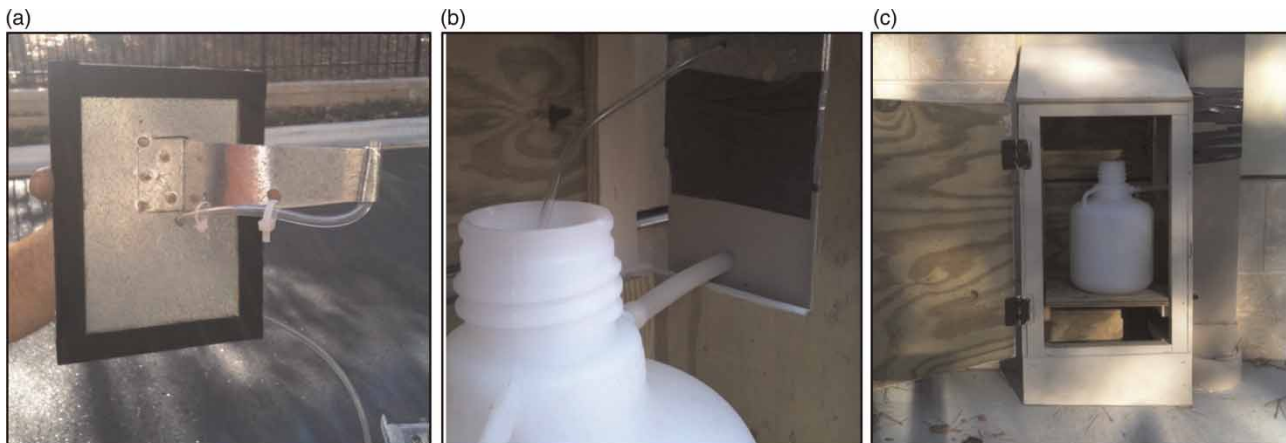
**Figure 2** | Underground Tank 1.

dimensions of this tank were 4.2 m wide by 12.9 m long by 1.5 m tall. Water in UT1 was used to irrigate the tree protection area through a drip irrigation system scheduled to cycle for 1 hour daily. Parking lot runoff and rooftop runoff exceeding the capacity of the RWH tanks drained to an underground detention and infiltration system beneath the parking lot.

UT1 contained a 10-mm diameter drawdown orifice at the bottom of the tank that emptied within 5 days after a storm event. To irrigate the tree protection area, a submersible pump located approximately 0.2–0.3 meters above the bottom of UT1 pumps the water through drip irrigation lines. A 75- μ m filter was located on the drip valve assemblies of the irrigation line.

Monitoring

The inflow and outflow of UT1 were monitored to determine any water quality improvement. Representative inlet samples were collected at one of the four contributing downspouts to the tank. The inlet monitoring station included a flow diversion device constructed inside the downspout to capture flow-proportional samples, a 20-liter sampling bottle fitted with an overflow tube, and a box to house the sampling bottle (Figure 3). The flow diversion device consisted of 3.2-mm diameter vinyl tubing supported by an aluminum arm, which was used to place the bubbler tubing in the interior corner of the downspout, where high flow was observed (Figure 3(a)). This device captured a

**Figure 3** | Inlet (downspout) monitoring setup, from left: (a) flow diversion device, (b) connection of downspout to sampling bottle, and (c) monitoring box.

small portion of each storm event, partially filling the 20-liter sample bottle with a flow-proportional fraction of the influent stormwater (Figure 3(b)). The 20-liter bottle was never completely filled by a storm.

The outlet monitoring station was a passive design located in the tree preservation area beneath a drip irrigation line. Because the drip irrigation system routinely ran for 1 hour daily, a 20-liter sampler bottle fitted with a funnel (Figure 4) collected a representative sample of water exiting the irrigation system. Outflow sampling occurred within 1 day of a storm event. Collecting water from one perforation in the drip irrigation line produced a sufficient sampling volume for analysis.

An ISCO 674 tipping-bucket rain gage located adjacent to the monitoring site recorded precipitation depth and intensity. A manual rain gage that measured precipitation depth calibrated the automatic rain gage. On average, a correction coefficient for adjustment of the automatic rain gage data was 1.15, and the adjustment was independent of rainfall intensity.

Sampling and laboratory analysis

Flow-weighted, composite influent water quality samples were taken throughout each runoff-producing storm event. Effluent samples were collected at the completion of each event during a 1-hour irrigation period. Samples were collected within 24 hours of the cessation of rainfall and were chilled to $<4^{\circ}\text{C}$ until analyzed. Composite stormwater samples were split into three bottles: (1) 20 ml was filtered

through a 0.45-micron filter into a glass bottle to measure orthophosphate (Ortho-P), (2) a 250-ml pre-acidified (H_2SO_4) plastic bottle for all other nutrient forms, and (3) a non-acidified 1-liter plastic bottle for TSS. Malfunction of the irrigation system occurred from April 23 to June 13, 2012, causing a gap in collected data for the spring season.

Nitrogen species (total Kjeldahl nitrogen (TKN), total ammoniacal nitrogen (TAN), nitrite-nitrate (NO_x)), phosphorus species (TP, Ortho-P), and TSS were analyzed at the North Carolina State University Center for Applied Aquatic Ecology (CAAE) laboratory, approximately 18 km from site. Samples were analyzed using United States Environmental Protection Agency and standard methods (APHA *et al.* 1995). TN was calculated by summing concentrations of TKN and NO_x ; organic nitrogen (ON) was calculated by subtracting concentrations of TAN from those of TKN. Event mean concentrations (EMCs) below the practical quantitation limit (PQL) determined by the CAAE (27% occurrence) were assigned a value of one-half of the PQL for statistical purposes (Gilbert 1987). A soils analysis was conducted on May 15, 2013 using the hydrometer method (Gee & Bauder 1986).

Data analysis

Data analysis was performed with SAS[®] 9.3 software (SAS Institute, Inc. 2012) to statistically compare pollutant concentrations at the inlet and outlet of UT1. Normally distributed data were tested for statistical significance using the student's *t* test. Non-normal data were log-transformed; those

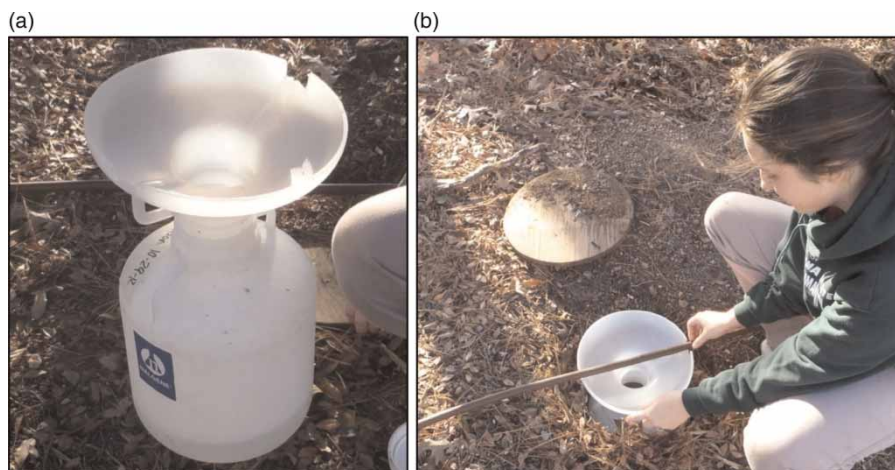


Figure 4 | Passive outlet (irrigation) monitoring station, from left: (a) sampling bottle with funnel and (b) monitoring station with irrigation line.

log-transformed data fitting a normal distribution were analyzed using the student's *t* test. All data were determined to have normal or lognormal distributions. Data were analyzed for statistical significance at the $\alpha = 0.05$ and $\alpha = 0.10$ levels.

RESULTS AND DISCUSSION

Precipitation characteristics

Water quality samples were collected from January 11–February 20, 2012 and July 10–December 18, 2012. During 2012, annual precipitation of 1,285 mm was 9% above the Raleigh, NC normal value of 1,179 mm. The 17 storm events sampled for water quality ranged in depth from 4.8–39.9 mm, with a mean and median event size of 18.1 and 14.9 mm, respectively. Sample collection occurred throughout the winter (six samples), summer (six samples), and fall (five samples) seasons.

Pollutant concentrations

Influent and effluent pollutant concentrations were compared for each of 17 monitored storm events (Table 2). Effluent TKN, TN, Ortho-P, and TP concentrations were either relatively equal or slightly higher in effluent concentrations than influent concentrations, although these differences were not significant. Significant ON addition

(+38%), NO_x reduction (–23%), and TSS reduction (–55%) were likely caused by settling and nitrogen cycle processes within the tanks. Outliers were observed in both the influent and effluent nutrient and sediment data sets; for purposes of data analysis, no outliers were removed from the data sets. Statistical testing for differences in RWH performance during the autumn, winter, spring, and summer seasons showed no significant results.

Nitrogen species

Though TN and TKN concentrations were not found to be statistically different between inflow and outflow, ON concentrations increased 38% ($p = 0.0460$), and those of NO_x decreased 23% ($p = 0.0189$); TAN increased 33%, significantly at the $\alpha = 0.10$ level (Figure 5). The reduction in NO_x EMCs may be a result of several processes occurring, including denitrification of NO_x into gaseous N₂ and/or dissimilatory nitrate reduction to ammonium (DNRA; Reddy & Delaune 2008). If the sole process of NO_x reduction was denitrification, a reduction of TN would have been observed; however, TN did not change. DNRA, the process by which anaerobic bacteria convert NO_x to TAN, may explain both the reduction in NO_x and the increase in TAN. Though dissolved versus particulate ON was not sampled, another possible process to explain TAN increase is conversion of particulate ON to dissolved ON to TAN. This, however is not supported by the increase in ON. DeBusk & Hunt (2014) observed a similar trend of NO_x

Table 2 | Mean observed influent and effluent EMCs and percent change

EMC (mg/L)	Influent ^a ($n = 17$)	Effluent ^a ($n = 17$)	Difference ^b	Normality	<i>p</i> -value	NC rooftops (influent) ^c	NC RWH (effluent) ^c
TKN	0.46	0.63	+ 36%	Normal	0.4943	0.89	0.47
TAN	0.24	0.32	+ 33%	Lognormal	0.0663	0.43	0.20
ON	0.22	0.31	+ 38%*	Lognormal	0.0460	0.46	0.27
NO _x	0.37	0.29	– 23%**	Normal	0.0040	0.50	0.28
TN	0.84	0.92	+ 10%	Normal	0.1502	1.56	0.78
Ortho-P	0.007	0.008	+ 14%	Lognormal	0.8938	–	–
TP	0.02	0.03	+ 74%	Lognormal	0.4966	0.03	0.02
TSS	5.44	2.42	– 55%*	Lognormal	0.0490	3.48	2.67

^aMedian values obtained herein.

^bPositive difference = addition, negative difference = reduction (inlet to outlet).

^cMedian values; DeBusk & Hunt (2014).

Statistically significant differences indicated by: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

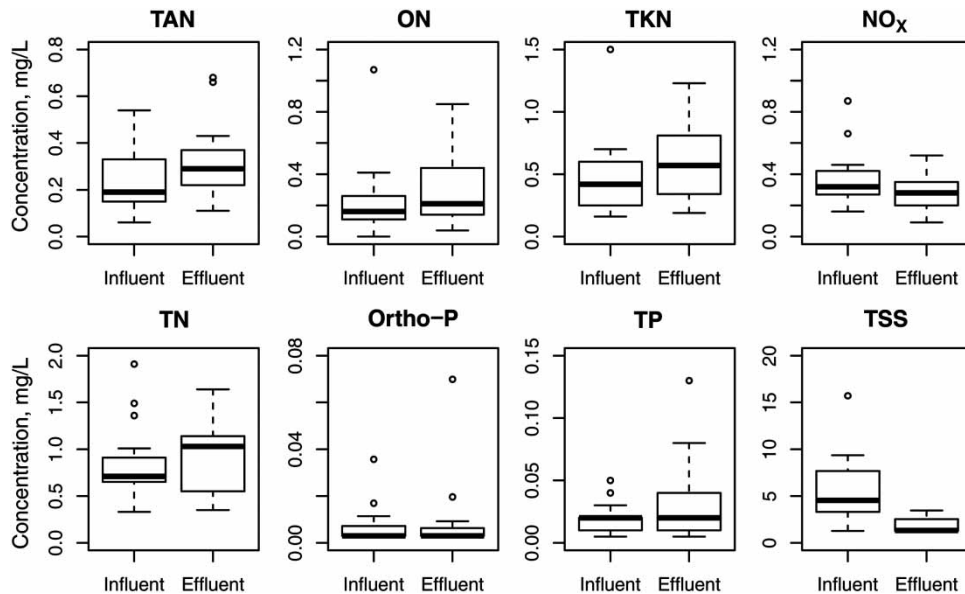


Figure 5 | Influent and effluent storm EMCs.

reduction and TAN increase in RWH systems in Raleigh, NC, attributing this nitrogen transformation to denitrification, DNRA, or conversion of ON to TAN.

For perspective, previous RWH and rooftop studies have reported comparable TN influent and effluent EMCs to those observed herein (DeBusk *et al.* 2014; Hathaway *et al.* 2008; Table 2). However, Despins *et al.* (2009) reported mean effluent EMCs ranging from 1.5 to 2.0 mg/L in Ontario, Canada, higher than the observed mean TN EMC herein. With the exception of NO_x, nutrient reduction was not observed in this RWH system due to low influent and effluent EMCs and possible ‘irreducible’ concentrations (concentrations of stormwater that an SCM would not be expected to reduce, given its pollutant removal unit processes; Strecker *et al.* 2001). The low nitrogen concentrations observed herein are suspected to be due to the lack of overhanging vegetation on this large two-storey roof, allowing little ON to be deposited on the roof. DeBusk & Hunt (2014) reported higher concentrations for all nitrogen species, and observed significant reductions of all nitrogen species concentrations. Effluent TN, ON, and NO_x EMCs observed herein were less than median EMCs for streams of ‘excellent’ or ‘good’ health, and were therefore not likely to negatively affect receiving waterways (McNett *et al.* 2010).

Phosphorus species

Neither TP nor Ortho-P was significantly different after passing through the tank (Table 2; Figure 5). The lack of phosphorus mitigation in this study was likely due to very low rooftop TP and Ortho-P EMCs (0.02 mg/L and 0.007 mg/L, respectively). Of the 17 storms sampled, three influent and four effluent TP EMCs were below the PQL of 0.01 mg/L. Similarly, Ortho-P EMCs were below the PQL of 0.006 mg/L for nine influent and 12 effluent storm events sampled. These results suggest potentially ‘irreducible’ concentrations of phosphorus species running off this rooftop (Strecker *et al.* 2001).

In Hathaway *et al.* (2008), TP EMCs for rainfall were 0.05 mg/L on average, approximately two times greater than both influent and effluent EMCs in this study. Bannerman *et al.* (1993) reported an average TP EMC of 0.20 mg/L for commercial rooftops, approximately 10 times the median EMC observed herein. Influent TP concentrations reported by DeBusk & Hunt (2014) had a median of 0.03 mg/L, approximately 1.5 times that observed herein. They were significantly reduced (by 15%), showing the potential of TP mitigation at higher EMCs (Table 2). Effluent TP EMCs were substantially less than those in streams of ‘excellent’ health ratings in the piedmont of NC (McNett *et al.* 2010).

Total suspended solids

Of the 17 storm events monitored, three influent and 14 effluent EMCs were below reported PQLs, indicating that despite clean influent, effluent TSS concentrations were still reduced (Figure 5). A mean TSS reduction of 55% was observed due to particle settling within the tank. The mean influent TSS EMC at this site (5.44 mg/L) was less than that reported at similar sites (Bannerman *et al.* 1993; Table 2).

Unlike biological and chemical nutrient removal processes, physical processes, such as particle settling, occur immediately upon entering the RWH system, allowing for potential TSS mitigation, even in circumstances of short detention time. The settling efficiency within a RWH tank depends on a number of factors, including particle size and water velocity. The rooftop median particle type was silt, with settling velocities (calculated using Stokes' Law) ranging from 4E-6 to 2E-3 m/s. Therefore, particle settling time ranged from 0.5 hours to 6 days, allowing for some sedimentation of particles before the tank is emptied via the drawdown orifice. The near complete absence of velocity within the tank aids sedimentation.

CONCLUSIONS

Although RWH systems are typically designed for runoff volume capture and use, some transformation of pollutant concentrations was observed in this RWH system. Significant TAN concentration increase (+33%), ON concentration increase (+38%), and NO_x concentration reduction (−22%) were likely due to nitrogen transformation, notably through the DNRA process. Settling of particles from rooftop runoff in the RWH tank yielded a TSS reduction of 67%, although TP, typically being a majority sediment-bound, did not significantly change. Although a majority of EMCs were not reduced in this case study, effluent NO_x, ON, TN, and TP EMCs were lower than median EMCs of streams of 'good' or 'excellent' health in the piedmont of NC (McNett *et al.* 2010). This RWH tank was successful at mitigating stormwater runoff to at-or-below typical rainfall and healthy stream EMCs. Were similar results found repeatedly, the impact of

development on receiving waterways might be partially mitigated. This case study suggests that RWH tanks can be important components in stormwater management systems designed to mitigate nutrient and TSS loads. The results, however, are not definitive even at this one site for all pollutants examined herein.

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