The Impact of On-Site Wastewater Treatment Systems on the Nitrogen Load and Baseflow in Urbanizing Watersheds of Metropolitan Atlanta, Georgia

C. Oliver[1], L.M. Risse[1], D. Radcliffe[2], M. Habteselassie[2], J. Clarke[3]

AUTHORS: [1] College of Engineering, The University of Georgia, Athens, Georgia 30602. [2] Department of Crop and Soil Sciences, The University of Georgia, Athens, Georgia 30602. [3]The United States Geological Survey, Atlanta Georgia 30360
REFERENCE: *Proceedings of the 2013 Georgia Water Resources Conference*, held April 10-11, 2013, at the University of Georgia.

Abstract. On-site wastewater treatment systems (OWTSs) are widely used in the Southeastern United States for municipal wastewater treatment. As urban and suburban populations increase, the use of OWTSs is expected to further increase. This region heavily depends on surface waters for its water supply, therefore, the impact of OWTSs on surface water quality and quantity must be investigated. Conventional OWTSs can be potential sources of N pollution for groundwater and streams that can cause human health concerns and stimulate algal growth resulting in eutrophication. The overall goal of this project is to determine the impact of OWTSs on the N load and baseflow in urbanizing watersheds of Ocmulgee and Oconee River basins in Georgia. This paper presents preliminary results of the differences in the N load and baseflow as well as other water quality indicators such as electrical conductivity (EC) and chloride (Cl^-) in streams of watersheds impacted by high (HD) and low density (LD) OWTSs. Synoptic samples and discharge measurements of 24 watersheds were taken 3 times per year in fall, spring, and summer under baseflow conditions. EC and Cl^- concentrations were significantly higher in HD OWTS watersheds for all three sampling events. N concentrations were not statistically different between HD and LD watersheds for all three sampling events. Baseflow measurements in the fall and spring were not statistically different between HD and LD watersheds, but summer measurements were significantly higher in the HD watersheds. The results indicate the presence of OWTS effluent in streams of watersheds with HD OWTSs, while N analysis indicates a reduction in concentration through dilution and denitrification. However, increased baseflow in watersheds impacted by HD OWTSs results in an increase in total N load. Further analysis is needed to accurately determine and quantify the impact of OWTSs on water quality and quantity at the watershed-scale.

INTRODUCTION

Water quality and quantity concerns have increased significantly in recent years as people continue to move into the Piedmont region of the Southeastern United States. The populations in this region that includes Alabama, Georgia, South Carolina, and North Carolina increased 7.5 to 18.5 percent from 2000 to 2010. Georgia, with an 18.3 percent increase, almost doubled that of the national average of 9.7 percent. Most of its growth occurred along the Interstate 85 corridor in Metropolitan Atlanta. This fourteen county district in the northern part of the state experienced a 23.3 percent increase in population, and the growth is expected to continue in the future. (US Census Bureau, 2010). The groundwater and surface water systems are well connected in the Piedmont, with each watershed acting as a unit due to the relatively impermeable underlying rock. Due to the limited availability of high yield wells, surface water withdrawals account for about 78 percent of the public water supply of Metropolitan Atlanta.(Clarke and Peck, 1991; Fanning, 2001).

On-site wastewater treatment systems (OWTSs) are widely used for municipal wastewater treatment throughout the Southeast. It is estimated that more than 30 percent of the homes in Georgia are on OWTSs which is higher than the national average of 23 percent (U.S.EPA, 2002). The number of OWTSs in Metropolitan Atlanta is estimated to be 526,000 which is 26 percent of the total housing units in the district (MNGWPD, 2006). The number of OWTSs is expected to increase as populations increase in this region because of the high costs of centralized systems to extend out to suburban populations. OWTSs are no longer considered a temporary solution to be replaced eventually by centralized collection and treatment (Oakley et al., 2010). Therefore, as populations in Metropolitan Atlanta increase and the use of OWTSs increases, their impact on surface water quality and quantity must be investigated.

Traditional OWTS can be potential sources of pollution for groundwater and surface water. Contaminations include nutrients such as nitrogen (N) and phosphorus (P), microbial contaminants, viruses, and hormones. Nitrogen is the primary nutrient and contaminant of concern for this study. High N concentrations can impact both human health and the environment. Elevated N concentrations (typically in the form of nitrate-N) in drinking water can be harmful to humans causing restriction of oxygen transport in the bloodstream. This can be potentially fatal for young infants or can cause problems during pregnancy as they lack the enzyme needed to correct the condition. Excess N can also cause over stimulation of growth of aquatic plants and algae that can clog water intakes, block light to deeper waters, and use up dissolved oxygen as they decompose. This results in eutrophication that can produce fish kills and a decrease in animal and plant diversity within the watershed (USGS, 2012).

Many studies have shown groundwater in residential areas with high density OWTSs to have high nitrate-N concentrations that are up to 4 times the drinking water limit of 10 mg L^{-1} set by the USEPA (Harman et al., 1996; Kaushal et al., 2006; Postma et al., 1992). Several studies have also indicated elevated nitrate-N concentrations in groundwater below or down gradient from properly maintained and functioning OWTSs especially after high precipitation events (Arnade, 1999; Bernhardt et al., 2008; Gold et al., 1990). Other studies have identified OWTSs as the dominant source of N pollution at the watershed scale in streams where the watershed is developed with neighborhoods dependent upon OWTSs (Burns et al., 2005; Hatt et al., 2004; Kaushal et al., 2006; Reay, 2004). There have also been studies to confirm the origin of nitrate-N concentration to be from OWTSs using source tracking techniques that geochemically fingerprint the source (Aravena et al., 1993; Lu et al., 2008; McQuillan, 2004; Silva et al., 2002).

Water quality performance requirements for OWTSs are not clearly defined because of uncertainty about the processes involved in groundwater discharging systems. Primary drinking water standards are typically addressed in code regulations only by requirements that the infiltration system be located a specified horizontal distance from the wellhead and vertical distance from the seasonally high water table (U.S.EPA, 2002). Most states estimate the minimum lot size for OWTSs that will protect drinking water wells from exceeding the 10 mg L^{-1} drinking water standard for N. However, in surface waters that are sensitive to nutrient inputs, the threshold concentrations can be significantly lower than the drinking water standard (U.S. EPA, 2010). TMDLs (Total Maximum Daily Loads) are also becoming important watershed management and planning strategies to minimize watershed contamination. A TMDL developed for Lake Allatoona, a large reservoir north of Atlanta, includes N limits and attributes part of the nutrient load to OWTSs in the watershed (GADNR, 2012). There is a need however, for a more accurate assessment of the N load to streams contributed from OWTSs.

While most studies investigate the impacts of OWTSs on water quality, their influence on groundwater recharge and baseflow in streams is also an important water management issue for urbanizing watersheds of Metropolitan Atlanta. Several studies have indicated that increased impervious surfaces and constructed channels due to urbanization decrease infiltration and baseflow and increase storm water runoff (Calhoun et al., 2003; Landers et al., 2007; Simmons and Reynolds, 1982). However, some studies have reported that rising groundwater levels from the combination of leaking water and waste water-supply mains and OWTSs drainage networks more than offset the effects of reduced infiltration and baseflow resulting from urbanization (Lerner, 2002; Yang et al., 1999). The specific effect of OWTSs on water quantity has been investigated by two studies, both of which found that baseflow in watersheds with high-density OWTSs was significantly greater than in watersheds with low-density OWTSs indicating that while suburban developments do accelerate the transport of storm water runoff into streams, OWTSs can change the expected effects of development on storm water runoff and groundwater recharge (Burns et al., 2005; Landers and Ankcorn, 2008).

A common assumption by some environmental officials in Georgia is that OWTSs can be considered consumptive use and therefore reduce the amount of water recharging surface waters in Georgia. In the original guidelines for developing a state-wide comprehensive water management plan, the state Environmental Protection Division stated that OWTSs should be considered 100 percent consumptive use (MNGWPD, 2006). However, as a result of the study done by Landers and Ankcorn (2008), they have revised their guidelines to say that the degree of consumptive use is not known, but assumed to be more consumptive than centralized systems with surface water discharges (MNGWPD, 2009). Therefore, there is a need to more clearly define the contribution of OWTSs to groundwater recharge and to the baseflow in the streams of Metropolitan Atlanta.

The object of this study is to determine the impact of OWTSs on the N load and the baseflow in urbanizing watersheds of Ocmulgee and Oconee River basins in Metropolitan Atlanta, Georgia. This paper presents preliminary results of the differences in the N load and baseflow as well as other water quality indicators in streams of watersheds impacted by high (HD) and low density (LD) OWTSs. Results from this study will inform OWTS users, the OWTS industry, as well as local and state planners about the impacts of OWTSs and their contribution to the N load and baseflow of streams.

STUDY AREA

The study area has been described in detail in Landers and Ankcorn (2008). The area is in the Southern Piedmont region of southeast Atlanta, Georgia and has a mean annual precipitation of about 50 inches (National Weather Service, 2008). The small watersheds selected for the site are in the Ocmulgee and Oconee River basins, which drain to the Altamaha River and the Atlantic Ocean. The watersheds range in area from 0.07 to 3.4 square miles with an average area of 0.96 square miles. Of the 24 watersheds selected, twelve are characterized as having high density OWTSs with the remaining twelve characterized as having low density OWTSs. A watershed with less than 100 OWTSs per square mile was considered as a LD watershed while watersheds with greater than 200 OWTSs per square mile was considered as a HD watershed (Table 1). Other watershed selection criteria used were geological setting, precipitation, climate, accurate baseflow measurement locations and available spatial datasets of natural, infrastructure, and water use characteristics. The study area and watershed boundaries are shown in Figure 1.

METHODS

Synoptic measurements of baseflow were taken concurrently with water sampling three times a year to capture the different (seasonal) flow conditions. The stream flow measurements for the 24 sites were measured within a 48 hour period, with no intervening rainfall. In addition to baseflow, basic water quality parameters such as temperature, pH, electrical conductivity, and dissolved oxygen were measured using a multi-parameter water quality sonde.

Water samples were collected during baseflow periods three times per year at the same time as the synoptic stream flow measurements. All collected stream samples were analyzed by the University of Georgia Environmental Services Laboratory for NH_4^+, NO_3^-, total Kjeldahl N (TKN), $\delta^{15}N$, and Cl^-.

Table 1: The characteristics of the study area watersheds in Gwinnett County, Georgia (Landers and Ankcorn, 2008)

Watershed ID (see fig. 2 for locations)	High density (HDS) or low density (LDS) of septic systems	Drainage area (mi^2)	Count of septic systems	Density of septic systems (per mi^2)	Median distance septic systems to stream (feet)	Watershed impervious area, (percent)	Mean watershed slope (percent)	Base-flow yield, October 16–17, 2007 ($[ft^3/s]/mi^2$)	Specific conductance (µS/cm)
1	LDS	3.24	70	22	534	4.2	8.8	0.140	42
2	LDS	0.60	15	25	415	3.3	10.6	0.378	72
3	LDS	1.03	37	36	534	4.3	8.5	0.178	42
4	LDS	0.24	22	93	563	11.6	7.3	0.146	39
5	LDS	0.57	30	52	281	5.4	5.8	0.068	60
6	LDS	2.04	82	40	353	4.1	6.5	0.087	75
7	LDS	0.43	20	46	295	6.3	10.6	0.402	52
8	LDS	0.49	22	45	309	3.0	9.2	0.147	67
9	LDS	1.14	81	71	522	7.8	7.7	0.174	56
10	LDS	1.70	152	89	389	7.3	8.3	0.228	55
11	LDS	1.62	105	65	392	7.6	7.8	0.162	64
15	LDS	0.65	62	96	460	15.2	4.6	0.105	59
12	HDS	1.27	378	299	344	12.3	9.1	0.454	55
13	HDS	3.40	779	229	383	13.2	8.0	0.196	59
14	HDS	0.67	245	366	341	16.1	8.5	0.464	62
16	HDS	1.00	486	485	326	26.4	5.7	0.177	77
17	HDS	0.65	384	595	454	20.1	7.5	0.568	82
18	HDS	0.38	302	797	494	18.4	7.4	0.463	89
19	HDS	0.07	72	965	346	20.3	7.8	0.729	96
20	HDS	0.21	159	752	273	18.3	6.0	0.338	43
21	HDS	0.44	246	555	208	17.5	8.6	0.280	116
22	HDS	0.75	304	406	206	18.9	7.0	0.089	53
23	HDS	0.20	120	604	213	18.4	7.3	0.120	94
24	HDS	0.26	172	656	179	20.0	7.6	0.373	91
Mean	**LDS**	**1.15**	**58**	**57**	**421**	**6.7**	**8.0**	**0.185**	**57**
Mean	**HDS**	**0.78**	**304**	**559**	**314**	**18.3**	**7.5**	**0.354**	**76**

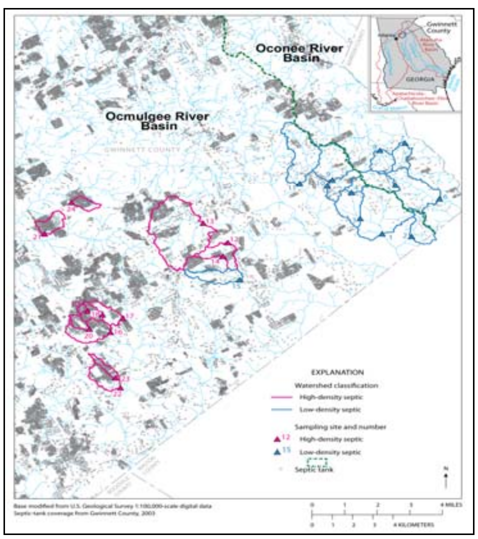

Figure 1: Location of the study area, 24 watershed boundaries, sampling sites and OWTSs in Gwinnett County, Georgia (Landers and Ankcorn, 2008).

The hypothesis was that watersheds impacted by HD OWTSs will have a higher N load and a higher baseflow when compared to watersheds with LD OWTSs. Nitrate-N (NO_3^-) concentrations were expected to be significantly higher in HD OWTS watersheds because it is considered quite mobile in soils and can be leached to groundwater where drinking water wells and surface water supplies may be contaminated.

The amount of N contributed from conventional OWTSs is dependent on the removal efficiency of the system through denitrification and dilution. Chloride (Cl^-) was used as a conservative tracer to observe N transformations and the effect of dilution within the watersheds. Cl^- is a non-reactive solute that is not subject to transformation by microbial activity, and it has been shown to increase linearly from a background of about 20 mg L^{-1} with increasing NO_3^- concentrations. Cl^- also serves as a good indicator parameter for OWTS impacts because it is present in all sewage (McQuillan, 2004). Therefore Cl^- concentrations were expected to be significantly higher in HD OWTS watersheds.

The concentration of ^{15}N a stable isotope of N, was also observed in order to identify the sources of N within the watersheds. Biological organisms preferentially use the lighter isotope of nitrogen, ^{14}N, rather than the heavier isotope, ^{15}N, for respiration and assimilation because the chemical bonds of lighter isotopes are generally broken down easier than those of heavier isotopes. As a result, ^{14}N becomes concentrated in cell mass while ^{15}N becomes concentrated in the residual N source and in human and animal wastes. NO_3^- in groundwater that has been denitrified by microbes or originates from human or animal waste is enriched with ^{15}N (McQuillan, 2004). Distinct isotopic compositions have been identified to characterize N of different origin so that the molar ratio of ^{15}N to ^{14}N can be measured to distinguish between human waste, animal waste, and synthetic fertilizers (Aravena et al., 1993). Therefore, ^{15}N concentrations were expected to be significantly higher in HD OWTS watersheds.

RESULTS AND DISCUSSION

Synoptic samples and discharge measurements of 12 LD and 12 HD OWTS watersheds were taken 3 times in November 2011, March 2012, and July 2012 under baseflow conditions. Electrical conductivity (EC; Figure 2) and chloride (Cl; Figure 3) concentrations were significantly higher in streams of watersheds impacted by HD OWTSs for all three sampling periods (p-value < 0.05). All forms of nitrogen (N) including nitrate (NO_3^-; Figure 4), ammonium (NH_4^+), total Kjeldahl N (TKN), and $\delta^{15}N$ concentrations were not statistically different between LD and HD OWTS watersheds for all three sampling periods (p-value > 0.05). Baseflow measurements in November 2011 and March 2012 were not statistically different between LD and HD OWTS watersheds, but July 2012 measurements were significantly higher in streams of watersheds impacted by HD OWTSs (p-value < 0.05; Figure 5).

EC and Cl^- results indicate the presence of OWTS effluent in streams of watersheds with HD OWTSs. Baseflow results also indicate the presence of OWTS effluent in HD OWTS watersheds despite the lack of difference between watersheds in the first two sampling events. An important watershed characteristic is the percentage of impervious surfaces. As shown in Table 1, the HD OWTS watersheds are significantly higher in impervious surfaces (p-value < 0.05). Watersheds with a high percentage of impervious surfaces are expected to have a lower baseflow than watersheds with a low percentage of impervious surfaces due to less infiltration and more runoff. However, the results show no difference in the baseflow in November 2011 and March 2012 and a higher baseflow in July 2012 indicating an increase in baseflow due to OWTS effluent.

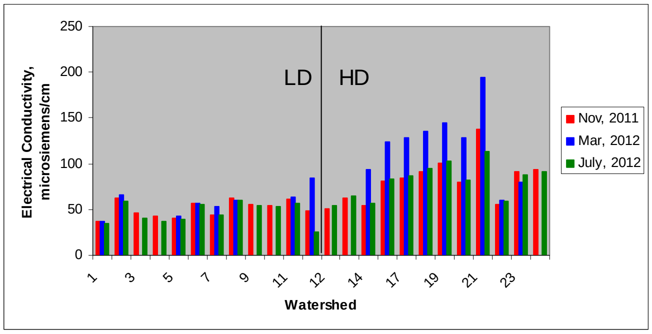

Figure 2: Electrical conductivity concentrations in streams of watersheds with LD and HD OWTSs in Fall 2011, Spring 2012, and Summer 2012.

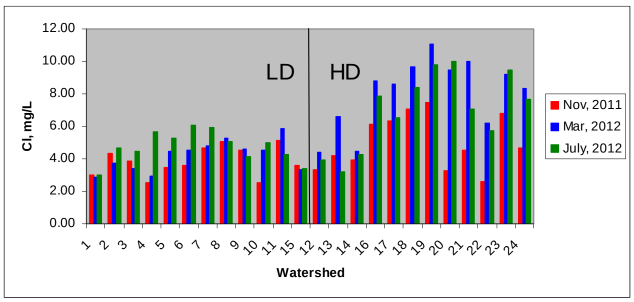

Figure 3: Chloride concentrations in streams of watersheds with LD and HD OWTSs in Fall 2011, Spring 2012, and Summer 2012.

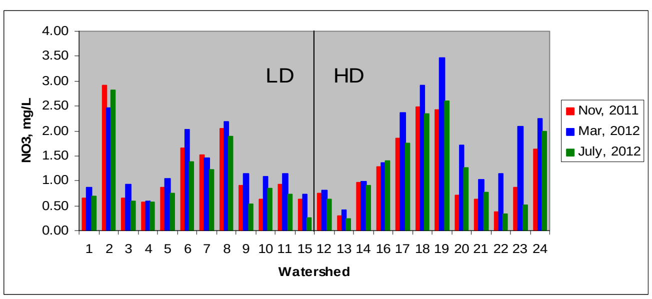

Figure 4: Nitrate-N concentrations in streams of watersheds with LD and HD OWTSs in Fall 2011, Spring 2012, and Summer 2012.

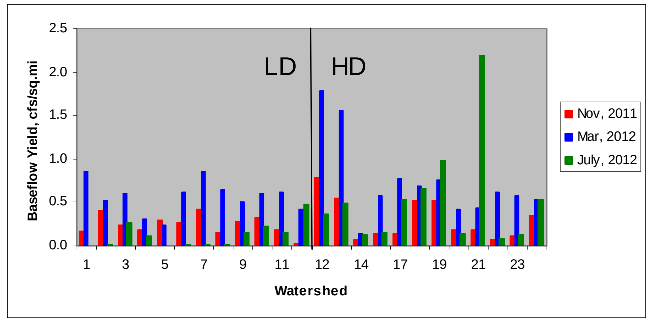

Figure 5: Baseflow measurements in streams of watersheds with LD and HD OWTSs in Fall 2011, Spring 2012, and Summer 2012.

N results indicate a reduction in concentration through a combination of dilution and dentrification in OWTS drainfields and along flow paths to streams. However, increased baseflow in the watersheds impacted by HD OWTSs results in an increase in the N load as shown in Figure 6. The N load in the HD OWTS watersheds was significantly higher during the July 2012 sampling event due to the significantly higher baseflow (p-value < 0.05).

Cl^- regression analysis showed a linear increase in concentration as a function of OWTS density within the watershed as shown in Figure 7 from July 2012 ($R^2 = 0.6751$). Results are similar for the November 2011 and March 2012 sampling events which indicate an increase in the presence of OWTS effluent with an increase in OWTS density. NO_3^- regression analysis of concentration as a function of OWTS density showed a weak correlation as shown in Figure 8 from July 2012 ($R^2 = 0.1724$). Results are similar for the November 2011 and March 2012 sampling events. However, some LD OWTS watersheds appear to have high NO_3^- concentrations that may be due to agricultural runoff, animal wastes, or leaking sewer lines. ^{15}N regression analysis, as shown in Figure 9, indicates the presence of NO_3^- derived from human or animal wastes in some LD OWTS watersheds. Therefore, further analysis is needed to identify other sources of N within the watersheds in order to correctly determine the impact of OWTSs on the N load within the watershed.

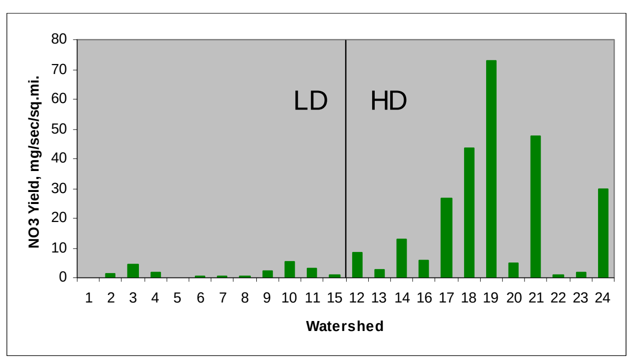

Figure 6: Nitrate yield (load per unit area) in streams of watersheds with HD and LD OWTSs in July 2012.

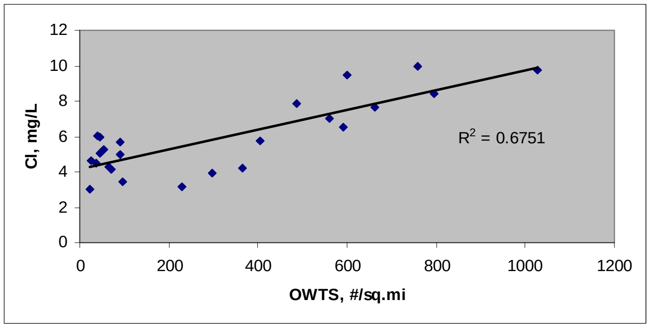

Figure 7: Chloride concentration as a function of OWTS density within the watershed in July 2012.

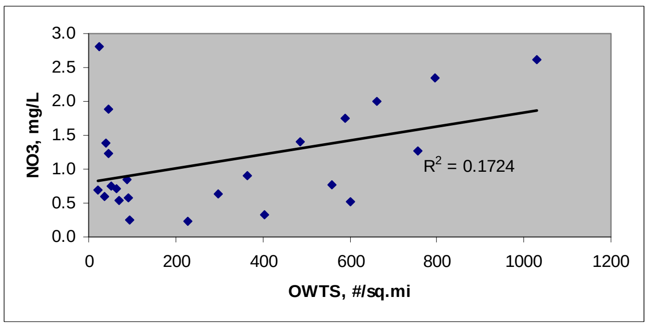

Figure 8: Nitrate-N concentration as a function of OWTS density within the watershed in July 2012.

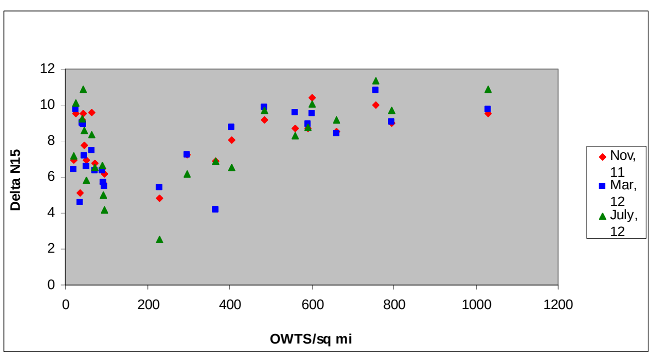

Figure 9: $\delta^{15}N$ concentrations as a function of OWTS density within the watershed in Fall 2011, Spring 2012, and Summer 2012.

CONCLUSION

The results indicate the presence of OWTS effluent in streams of watersheds impacted by HD OWTSs. N analysis indicates a reduction in concentration through a combination of dilution and denitrification within the watershed. However, an increase in baseflow results in an increase in N load. Further analysis is needed to identify all sources of N within the watersheds, to quantify the OWTS contribution to the N load and baseflow in the watersheds of the region, and to accurately determine the impact of OWTSs on water quality and water quantity at the watershed-scale.

REFERENCES

Aravena, R., M. L. Evans, and J. A. Cherry. 1993. Stable Isotopes of Oxygen and Nitrogen in Source Identification of Nitrate from Septic Systems. *Ground Water* 31(2):180-186.

Arnade, L. J. 1999. Seasonal Correlation of Well Contamination and Septic Tank Distance. *Ground Water* 37(6):920.

Bernhardt, E. S., L. E. Band, C. J. Walsh, and P. E. Berke. 2008. Understanding, Managing, and Minimizing Urban Impacts on Surface Water Nitrogen Loading. *Annals of the New York Academy of Sciences* 1134:61-96..

Burns, D., T. Vitvar, J. J. McDonnell, J. Hassett, J. Duncan, and C. Kendall. 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology* 311(1-4):266-281.

Calhoun, D. L., E. A. Frick, and G. R. Buell. 2003. Effects of urban development on nutrient loads and streamflow, upper Chattahoochee River Basin, Georgia, 1976-2001. *Proceedings - Georgia Water Resources Conference* 2003.

Clarke, J. S., and M. S. Peck. 1991. Ground-Water Availability in the South Metropolitan Atlanta Region, Georgia. In *1991 Georgia Water Resource Conference*. Athens, GA: Georgia Institute of Technology Institute of Natural Resources.

Fanning, J. L. 2001. Public-supply water use in the Metropolitan Atlanta, Georgia area, 1995-2000. *Proceedings - Georgia Water Resources Conference* 2001:782-782.

GADNR. 2012. Draft Total Maximum Daily Load Evaluation for Lake Allatoona in the Coosa River Basin for Chlorophyll a. The Georgia Department of Natural Resources, ed.

Gold, A. J., W. R. DeRagon, W. M. Sullivan, and J. L. Lemunyon. 1990. Nitrate-nitrogen losses to groundwater from rural and suburban land uses. *Journal of Soil and Water Conservation* 45(2):305-310.

Harman, J., W. D. Robertson, J. A. Cherry, and L. Zanini. 1996. Impacts on a sand aquifer from an old septic system; nitrate and phosphate. *Ground Water* 34(6):1105-1114.

Hatt, B. E., T. D. Fletcher, C. J. Walsh, and S. L. Taylor. 2004. The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams Stream Pollutants and Urbanization. *Environmental Management* 34(1):112-124.

Kaushal, S. S., W. M. Lewis Jr, and J. H. McCutchan Jr. 2006. Land Use Change And Nitrogen Enrichment

Of A Rocky Mountain Watershed. *Ecological Applications* 16(1):299-312.

Landers, M. N., and P. D. Ankcorn. 2008. Methods to evaluate influence of onsite septic wastewater-treatment systems on base flow in selected watersheds in Gwinnett County, Georgia, October 2007. U. S. Geological Survey : Reston, VA, United States. United States.

Landers, M. N., P. D. Ankcorn, and K. W. McFadden. 2007. Watershed effects on streamflow quantity and quality in six watersheds of Gwinnett County, Georgia. U. S. Geological Survey : Reston, VA, United States. United States.

Lerner, D. N. 2002. Identifying and quantifying urban recharge; a review. *Hydrogeology Journal* 10(1):143-152.

McQuillan, D. 2004. "Ground-Water Quality Impacts From On-Site Septic Systems". *Proceedings, National Onsite Wastewater Recycling Associations, 13th Annual Conference*.

MNGWPD. 2006. Septic Systems Status and Issues Working Paper, Metropolitan North Georgia Water Planning District. Available at: http://www.northgeorgiawater.org/files/district_septic_report_mar2006.pdf.

MNGWPD. 2009. Section 4: Wastewater Management Issues, Metropolitan North Georgia Water Planning District Wastewater Management Plan. Available at: http://www.northgeorgiawater.org/plans/wastewater-management-plan.

National Weather Service. 2008. 2007 climate summary for north and central Georgia: Forecast Office Peachtree City, Georgia. National Oceanic and Atmospheric Administration. Available at: http://www.srh.noaa.gov/ffc/.

Oakley, S. M., A. J. Gold, and A. J. Oczkowski. 2010. Nitrogen control through decentralized wastewater treatment: Process performance and alternative management strategies. *Ecological Engineering* 36(11):1520-1531.

Postma, F. B., A. J. Gold, and G. W. Loomis. 1992. Nutrient and microbial movement from seasonally-used septic systems. *Journal of Environmental Health* 55(2):5-10.

Reay, W. G. 2004. Septic tank impacts on ground water quality and nearshore sediment nutrient flux. *Ground Water* 42(7):1079-1089.

Silva, S. R., P. B. Ging, R. W. Lee, J. C. Ebbert, A. J. Tesoriero, and E. L. Inkpen. 2002. Forensic Applications of Nitrogen and Oxygen Isotopes in Tracing Nitrate Sources in Urban Environments. *Environmental Forensics* 3(2):125.

Simmons, D. L., and R. J. Reynolds. 1982. Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. *Water resources bulletin* 18(5):797-805.

U.S.EPA. 2010. Water Qulity Standards for the State of Florida's Lakes and Flowing Waters. Available at: http://water.epa.gov/lawsregs/rulesregs/florida_factsheet.cfm.

US Census Bureau. 2010. United States Census 2010. Available at: http://2010.census.gov/2010census/index.php.

USGS. 2012. U.S. Geological Survey, Nitrogen and Water. Available at: http://ga.water.usgs.gov/edu/nitrogen.html.

Yang, Y., D. N. Lerner, M. H. Barrett, and J. H. Tellam. 1999. Quantification of groundwater recharge in the city of Nottingham, UK. *Environmental Geology [Berlin]* 38(3):183-198.