NC WATER RESOURCES RESEARCH INSTITUTE

Report No. 484

A WATERSHED MODEL TO UNDERSTAND GROUNDWATER AND SURFACE WATER INTERACTIONS TO SUPPORT SEWER UTILITY RESILIENCE AT THE JACKSONVILLE N.C. FOREST WATER RE-USE FACILITY

By
Elizabeth Guthrie Nichols
Nancy Elizabeth Gibson
Katherine Lee Martin

Department of Forest and Environmental Resources
North Carolina State University
Raleigh, North Carolina

And

Ge Sun

Research Hydrologist, U.S.D.A. Forest Service
Southeast Climate Change Center
Professor, Department of Forestry and Environmental Resources
North Carolina State University

wrri.ncsu.edu
NC WATER RESOURCES RESEARCH INSTITUTE

UNC-WRRI-484

The research on which this report is based was supported by funds provided by the North Carolina General Assembly and/or the US Geological Survey through the NC Water Resources Research Institute.

This report fulfills the requirements for a project completion report of the North Carolina Water Resources Research Institute. The authors are solely responsible for the content and completeness of the report.

WRRI Project No. 18-01-W
April 2019

wrri.ncsu.edu
NC WATER RESOURCES RESEARCH INSTITUTE

A Watershed Model to Understand Groundwater and Surface Water Interactions to Support Sewer Utility Resilience at the Jacksonville N.C. Forest Water Re-Use Facility.

Proposed start: March 1, 2018
Proposed end date: December 31th, 2018

Project 2017-3027

NCSU Water Resources Research Institute: $10,000

Elizabeth Guthrie Nichols, Ph.D.
Professor
North Carolina State University
Department of Forest and Environmental Resources
Campus Box 8006
Raleigh, NC 27695
919-513-4832
egnichol@ncsu.edu

Nancy Elizabeth Gibson
M.S. Natural Resources
North Carolina State University
Department of Forestry and Environmental Resources
Campus Box 8006
Raleigh, NC 27695
704-305-1411
negibson@ncsu.edu

Katherine Lee Martin, Ph.D.
North Carolina State University
Department of Forest and Environmental Resources
katie_martin@ncsu.edu

Ge Sun, Ph.D.
Research Hydrologist, U.S.D.A. Forest Service
Southeast Climate Change Center
Professor, Department of Forestry and Environmental Resources
North Carolina State University
gesun@ncsu.edu

Abstract

A Watershed Model to Understand Groundwater and Surface Water Interactions to Support Sewer Utility Resilience at the Jacksonville N.C. Forest Water Re-Use Facility.

The goal of this project was to develop a comprehensive, deterministic, distributed and physically-based hydrologic model (MIKE-SHE) to provide the City of Jacksonville (NC) with historical and current visualizations of how their current municipal wastewater treatment system, a forest land application site (FWR), functions hydrologically among the seasons in response to weather, forest age, and forest management. Project objectives were to use the model to (1) forecast FWR response under different scenarios of weather extremes and (2) to forecast FWR response under different regimens of water reuse or forest composition using a water balance approach. The City of Jacksonville is exploring strategies to increase FWR capacity for future demand.

Simulated evapotranspiration (ET) and water table depth (WTD), using MIKE-SHE and twenty years of measured precipitation and irrigation data from the land treatment facility, were used to calculate drainage (runoff and lateral flow) across the site. Irrigation impacted ET and WTD to the greatest extent for forest areas surrounded by irrigation fields but caused little change in annual ET. Forest water use was relatively unchanged by irrigation, and annual watershed drainage increased proportionally to irrigation input. The drivers of on-site drainage were rainfall and the amount of irrigation. In wet years, ET and groundwater levels remained constant while drainage increased in response to rainfall and irrigation. WTD in wells surrounded by wastewater irrigation remained consistently closer to the surface than wells with only partial irrigation nearby.

The model under-predicted WTD for wells on the site’s exterior during below average rainfall periods. Groundwater withdrawal for agricultural use by adjacent landowners may explain this discrepancy. Extreme rainfall events, such as Hurricane Florence, resulted in high volumes of drainage but rapid recovery of groundwater storage in the FWR. The model provided insight to management practices that could increase FWR efficiency and flexibility for managing variable weather with climate change. One observation of the model was that current increases in irrigation volumes from winter application volumes to higher summer application volumes lag behind ET. Hence, one management option to increase irrigation capacity is to increase irrigation volume earlier in March rather than May. A sensitivity analysis of rooting depth and leaf area index to water use showed that rooting depth mattered more for water use than LAI. Forest management practices such as bedding for replanting would improve rooting depth of trees.

Nancy Gibson presented project results to the City of Jacksonville in March 2019. COJ was very excited that project results support current operation perspectives that the FWR could treat more wastewater if allowed more flexibility to land apply when conditions are optimal rather than prescribed volumes per week. Model observations that irrigation does not limit FWR ET and that rainfall drives FWR export of water were key outcomes that resonated with city officials and operators. Project results will be provided as an executive summary for the City of Jacksonville personnel to use in discussions with NCDEQ as both organizations discuss revised permits to avoid emergency spraying for extreme storms. This study has shown that these unique forest systems offer insights to water balance dynamics in irrigated forests and forest resiliency to extreme hydraulic loading that can be of use to regional wastewater land treatment systems for North Carolina.

Acknowledgments

This work was funded by the USDA Water for Agriculture grant NIFA 2016-68007-25069 with USGS WRRI 104(b) grant funding Project 2017-3027. We also thank the City of Jacksonville, NC for their support and assistance, and DHI Technologies for allowing their student license of MIKE SHE hydrological model.

1. Introduction.

In southeastern U.S. coastal communities, the sustainable management of forests and water resources is complicated by increased human population growth and climate change. Population growth in this region is expected to grow by 68 percent by the year 2060 (Klepzig et al 2014). Rainfall intensity and duration will increase due to increased temperatures, and salt water intrusion will accelerate due to sea level rise and excessive groundwater withdrawal (Webster et al 2014; Manda & Klein 2014). Another challenge to coastal North Carolina communities is growing demand for municipal wastewater treatment. North Carolina is unique among the southeastern U.S. states in its utilization of land treatment for municipal wastewater treatment. Fifty-one municipalities use forest systems to treat primary and secondary-treated municipal wastewater (Nielsen, 2012). These permitted facilities irrigate municipal wastewater onto forests to absorb nutrients and recharge groundwater (Birch et al., 2016, Nichols, 2016). Most facilities have land-applied wastewater for several decades with annual wastewater irrigation amounts equivalent to average annual rainfall (Birch et al., 2016). There are no quantitative studies on the hydrologic impacts of these green infrastructure systems post-installation nor any evaluations of their response to chronic hydraulic loading or extreme storm events such as hurricanes.

North Carolina’s forest water reuse (FWR) systems utilize slow-rate irrigation to land apply municipal wastewater across a variety of hardwood and softwood forests at a lower cost of treatment to other conventional wastewater treatment methods (Muga & Mihelcic 2008). FWRs provide additional benefits such as ecosystem services, wildlife habitat, nutrient removal, carbon sequestration, woody biomass production, and water regulation for water quality and water quantity (Nichols 2016). Recent efforts have quantified the export of emerging contaminants of concern (CECs) from FWR irrigation to on-site groundwater and surface waters (McEachran et al. 2017) and observed lower CEC concentrations in surface waters downstream of a FWR system versus conventional tertiary-treatment wastewater plant (McEachran et al. 2018). Stable isotopic modeling of wastewater, rainfall, groundwater, and surface waters demonstrated that the fraction of wastewater present in FWR systems varies with rainfall. The wastewater fraction in shallow groundwater and surface waters ranged from 50% to 76% and 3% to 58%, respectively, as dry conditions increased (Birch et al, 2016). There are no studies that have examined the effects of irrigated, coastal forest systems on watershed water balances and evapotranspiration (ET), drainage, and groundwater level dynamics.

Assessing the hydrologic impact of these green infrastructure systems is the first step toward understanding the impacts of irrigation on forests. Prior studies have shown that southern, coastal-plain forest hydrology has dynamic drainage in response to rainfall; runoff coefficients vary substantially from less than 10% in dry years to more than 50% in wet years (Harder et al 2007). The shallow water table is responsive to drought and wet periods although water surplus above potential evapotranspiration is the long-term trend for coastal areas (Amatya et al 2016). Groundwater and surface water in the coastal plain are highly connected with groundwater contributing up to 37% of stream water in the dormant season with dry antecedent soil moisture conditions (Garrett et al 2012). ET (>70% precipitation) represents the major water loss from forest systems in the lower coastal plain region and is greater than drainage (Sun et al., 2010). Even with variable rainfall, ET remains stable due to accessible shallow groundwater that is common to coastal plain geography (Liu et al 2018).

Southern coastal forests are subject to extreme climate variation from drought to tropical cyclones, and climate change is expected to increase temperatures and potential ET while decreasing groundwater levels and streamflow (Dai et al 2011, McNulty et al 2013). Coastal forest ET appears to be resilient against drought (Liu et al. 2018), but how coastal forest ET responds to excess water conditions is unclear. Prior studies have shown that storms generate the greatest drainage when forest conditions are wet and the water table is high (La Torre Torres et al 2011, Epps et al 2013). FWR systems can exist in a chronic state of wet forest conditions even for average annual rainfall conditions due to the constant need to irrigate wastewater. Understanding how irrigation impacts ET, water table levels, and runoff at FWRs is important to current operation management for wastewater treatment and forest regenerations well as anticipated climate variability and climate extremes. Annual and seasonal water balances are important tools to evaluate the hydrological response of FWR systems to rainfall variability and to understand FWR climate resiliency to extreme climate events such as Hurricane Florence.

This study used process-based hydrological modeling as a tool to estimate hydrologic responses to forest irrigation for the last twenty years at the largest FWR facility in North Carolina and second largest, slow-rate FWR facility in the U.S.A. ET and water table depth (WTD) were estimated for both irrigated and non-irrigated conditions in order to calculate drainage in the water balance model across seasons and under different leaf area index (LAI). Drainage was defined as the combination of surface runoff and lateral groundwater drainage to surface waters. The water balance was calculated monthly and annually for the study period. We hypothesized:
1. Irrigation would increase ET, elevate the water table, and increase drainage.

2. Sub catchments irrigated with wastewater will have consistent groundwater flow paths while non-irrigated sub catchments flow paths will vary more with precipitation inputs.
This hypothesis drives questions that addresses whether the amount of irrigation plus rainfall effects groundwater flow paths historically and during extreme weather events? Whether streamflow in the non-irrigated areas of the watershed is variable with rainfall? Is there a threshold at which the maximum amount of baseflow is supplied to surface waters? Do thresholds differ by soil qualities and forest composition?

3. Increased forest productivity (LAI) will correlate to increased groundwater storage.
Is streamflow greater when the forest is younger? How has forest age affected groundwater surface water interactions given major soil types and irrigation rates? Can alternative forests with different LAI better manage excessively wet conditions and alter thresholds for baseflow?

4. Potential groundwater extraction will depend on pumping well location on site.
How does proximity of extraction wells to surface waters impact baseflow thresholds?
We expected that the irrigated site would become more saturated over time.

The objectives of this study were to: (1) construct a water balance model for the study sites using measured and simulated hydrologic data; 2) test the model for estimating ET and WTD in irrigated and non-irrigated conditions; (3) evaluate and characterize the impacts of wastewater irrigation to annual and monthly ET, WTD and drainage across climate variability; (4) forecast FWR response under different scenarios of weather extremes; and (5) forecast FWR response under different regimens of water reuse or forest composition using a water balance approach.

Estimations of FWR response to climate extremes was actually observed in 2018. The eye of Hurricane Florence passed 30 miles southwest of the FWR site and delivered 25 inches of rainfall. FWR flooding was historic.

2 **Materials and Methods.**

2.1 Site Description.

The study site is located eight miles outside the City of Jacksonville in Onslow County, North Carolina (34°46'26.8"N 77°33'17.2"W). The watershed is delineated around Southwest Creek, a third-order headwater stream to the New River with 13 tributaries (Figure 1). The topography is relatively flat with a mean surface slope of 1.65% and ground surface elevations ranging from 3 to 8.5 meters (Birch et al 2016). The irrigated forest is primarily *Pinus taeda* (L.) but contains mixed hardwood species. Twenty-six soil types comprise the watershed. Baymeade fine sand (21%), Norfolk loamy fine sand (13%) and Foreston loamy fine sand (12%) are the three soil types which dominate the watershed. The average high and low temperatures are 10 to 23° C with 30-year annual rainfall of 1379 mm. The permitted maximum annual hydraulic loading of wastewater ranges from 1244 to 1590 mm per year and is based on soil types within each spray field. Large rainfall events can occur during the Atlantic hurricane season from June to November.

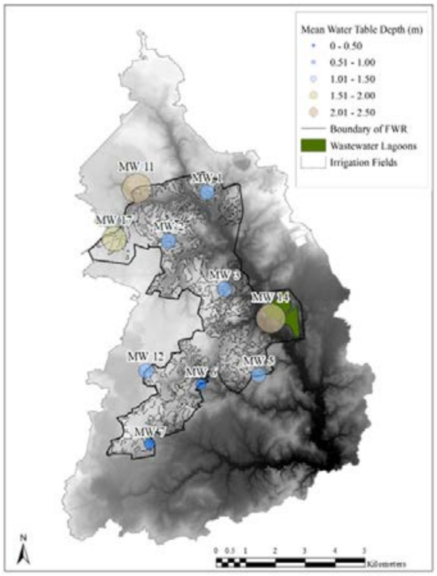

Figure 1. Map of 106 km^2 watershed and 30 km^2 FWR monitoring wells (MW) with mean water table depth (meters) for 2000 to 2018. Well 14 is not in the irrigated forest system.

The FWR facility has records dating back to its establishment in July 1998 that detail weekly wastewater and rainfall across the site at ten precipitation collectors and quarterly groundwater elevation measurements for the 16 monitoring wells distributed throughout the forest, site boundaries, and near the wastewater storage lagoons. Ten monitoring wells were instrumented with pressure transducer data loggers (Hobo U20L 13-foot water level loggers) beginning in August 2017. Daily PET was estimated using standard FAO Penman-Monteith equation for a grass reference for the study period (1998-2018) using observations from nearby weather stations. The leaf area index (LAI) is a parameter used in calculating actual evapotranspiration. For forested areas, LAI was estimated based on general monthly LAI for *Pinus taeda* plantations in the southeast (Liu et al 2018) while in non-forested areas monthly grass LAI was based on ground layer LAI.

2.2 MIKE SHE Model Descriptions

Evapotranspiration is a major loss of water in forest ecosystems but was not measured on site. Accurate measurement of ET would have required the site to be instrumented from the beginning of wastewater treatment operations. Models are useful tools in estimating ET in the absence of measurements and allow estimations of ET for scenario conditions such as non-irrigation at the water reuse forest. We adopted MIKE SHE, a modeling tool widely used for poorly drained coastal systems where the hydrology is controlled by a shallow water table. The model has been validated for applications in the Atlantic coastal plain (Zhang et al 2015, Dai et al 2011, Lu et al 2009). The MIKE SHE model simulated the complete ecohydrological cycle of the watershed in a distributed fashion with a spatial resolution of 1 km^2. The model was parameterized according to the guidelines established in the MIKE SHE Manual (MIKE 2017), including spatial data on topography, soils, vegetation, and temporal data on daily precipitation and Reference Evapotranspiration (ET_0) or PET.

Water Balance Model

The water balance was estimated under both non-irrigated and irrigated conditions to evaluate the impacts of irrigation management on drainage and the processes underneath the hydrologic changes. The water balance equation used in this study was:

$$Q=P+I-ET-\Delta S \qquad (1)$$

where Q is drainage, P is precipitation, I is irrigation, ET is evapotranspiration and ΔS is change in groundwater storage. This equation does not include deep seepage as a drainage factor (Harder et al 2007). Precipitation and irrigation are measured data provided by the FWR on a daily time step. ET is the actual evapotranspiration output from MIKE SHE, modeled on a daily time step. Change in groundwater storage is calculated as the change in head of the water table multiplied by specific yield. The change in head used was the depth to the phreatic surface output from the MIKE SHE model. In this study, the average specific yield manually calibrated in the MIKE SHE model soil layers (0.225) was used for the specific yield value in the change in storage calculation. The calibrated and validated MIKE SHE model was used to simulate irrigated ET and WTD, after which irrigation was removed from the model and a second model run simulated non-irrigated ET and WTD. The simulated daily results for ET and ΔS were used in the water balance equation to assess the long-term impact of irrigation on evapotranspiration, groundwater depth and drainage in the water reuse forest. All water balance components were calculated in millimeters. Equation 1 was used with MIKE SHE outputs from irrigated model. For the non-irrigated model, I in equation 1 was set to zero.

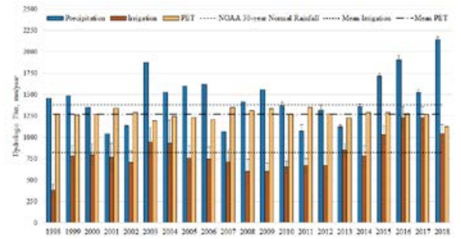

Figure 2. Annual average precipitation and irrigation volumes across site, along with the NOAA 30-year normal annual rainfall, 1379 mm (1981-2010).

3. **Results**

3.1 Climate, Irrigation, and Groundwater Level Dynamics

Precipitation, irrigation, and potential evapotranspiration (PET) show variability in annual (Figure 2) and seasonal (Figure 3) measurements from 1998 to 2018. The NOAA 30-year annual normal from 1981-2010 is 1379 mm, while the mean annual rainfall of the study period (1998-2018) is 1458 mm. For this study, above average years are defined as having one standard deviation above the mean annual rainfall (1766 mm) in addition to having above

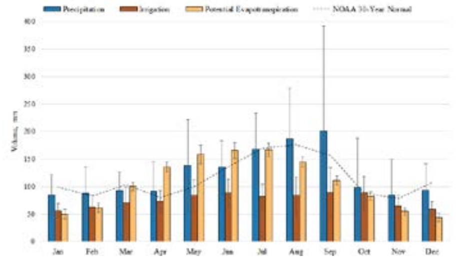

Figure 3. Monthly precipitation, irrigation and potential ET for years 1998 to 2018.

average mean annual irrigation (826 mm). Below average years are defined as years with one standard deviation below mean annual rainfall (1151 mm) in addition to having below average irrigation (826 mm). Mean rainfall trends higher from May to September and lower from October to April. In September 2018, Hurricane Florence brought 762 mm of rainfall to the study site over two days.

The FWR facility irrigated approximately 826 (± 205) mm treated water per year with annual mean irrigation exceeding 826 mm for 2003, 2004, 2013, and 2015-2018. The average annual irrigation is 58% of the NOAA 30-year mean and 55% of the mean rainfall for the study period. The mean monthly PET exceeds mean monthly irrigation from March to September, with exceedances ranging from 22 mm to 84 mm, while irrigation volumes are greater from May until October (83 – 90 mm) and are lower from November through April (57 – 73 mm). Annual potential evapotranspiration (PET) ranges from 27 mm to 187 mm less than the NOAA 30-year annual normal for rainfall but exceeds annual rainfall in 2001, 2002, 2007, 2011, and 2013. Although the PET was greater than precipitation at times, combined precipitation plus irrigation was 393 mm to 2058 mm greater than PET. On average, months with higher PET than precipitation occur from March to June, although the total monthly input to the site is always greater than the PET because of irrigation.

Groundwater levels for the site monitoring wells showed seasonal variation from 2000-2018 (Figure 4A) although levels among wells were not uniform (Figure 4B). Groundwater levels varied across the watershed and greater depths were observed for periods of drought and during high evapotranspiration summer months (Figure 4B). Recent daily groundwater level measurements (Figure 4C; Aug 2017- Sept 2018) fell within the range of historic quarterly levels. Figure 1 shows mean groundwater depth derived from quarterly measurements from 2000 to 2018 wherein depth trends upward toward the ground surface from the site perimeter to wells located in the center of the site. Depth levels are similar for wells except well 14 and wells 6, 7, 11, and 17. Located outside of the irrigated area and adjacent to the facilities' wastewater reservoirs, the position of Well 14 may explain its much lower water table depth. The relative mean depths of wells 6, 7, and 11, 17 reflect the topographical elevation of their respective locations. Wells 11 and 17 are adjacent to agricultural fields and may be influenced by groundwater extraction during water-short periods when crops are irrigated.

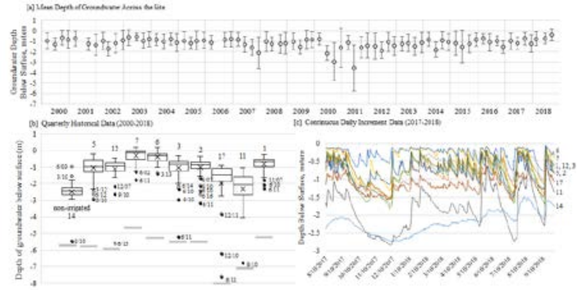

Figure 4. (a) Mean depth of groundwater below surface (m) based on quarterly measurements from 2000-2018 and daily measurements from 2017 to 2018. Box plots of groundwater depth below surface (m) for (b) quarterly measurements for individual wells and (c) daily average of 30-minute measurements by data loggers for monitoring wells on site. Well 14 is not irrigated. Total depths of each well are noted with a grey bar and month/year are provided for outlier groundwater depths for drought (black circles) and high evapotranspiration (grey circles).

3.2. MIKE SHE Model Calibration and Validation

Calibration and validation metrics are shown in Table 1. The model performance was evaluated using Pearson's R coefficient and Root Mean Square Error (MIKE 2017). Calibration correlations were over 0.6 R correlation (Pearson's) for every well (Table 1). The root mean square error (RMSE) values were acceptable, with the highest error seen in well 11. Well 6 had the lowest RMSE for the calibration period (Figure 5). Well 11 and well 17 had simulated water table depths that were consistently higher than the measured data, although their correlation was acceptable. The model was validated with 2010-2013 quarterly measurement data. The 2011 drought had low groundwater depth outliers for nearly every well. Reduced R correlation during the dry years of the validation period reflects dramatic decreases in groundwater levels during the drought. Groundwater depth returned to normal depths rapidly in the fall and winter, but the model did not capture that recovery response. As discussed before, Well 14 is uniquely located on the site; consequently, in the validation period, well 14 has a lower R correlations due to differences between model and actual measured groundwater depth in response to rainfall events. Overall, the model produced an acceptable fit of data for predicting evapotranspiration and groundwater levels.

Table 1. Calibration and Validation Metrics

	Validation 2010-2013		**Calibration 2014-2018**	
Monitoring Well	**RMSE**	**R**	**RMSE**	**R**
17	2.67	0.21	0.69	0.81
11	2.67	0.57	1.26	0.75
1	0.68	0.66	0.44	0.62
2	0.85	0.92	0.54	0.69
3	1.27	0.77	0.48	0.71
14 Non-irrigated	1.05	0.11	0.50	0.70
12	0.70	0.53	0.48	0.70
6	0.37	0.32	0.15	0.76
5	1.09	0.53	0.39	0.69
7	0.48	0.68	0.41	0.75

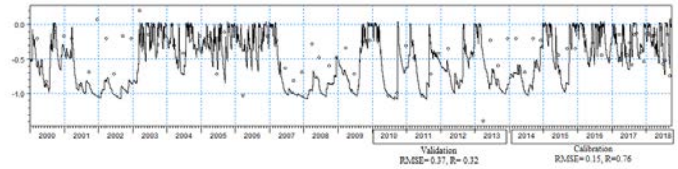

Figure 5. Simulated and measured data for Well 6.

3.3 Change in Water Balance due to Irrigation

The greatest change in the water balance due to irrigation is the increase in drainage (Q). When annual change in groundwater storage is negligible, the volume of drainage is the difference between ET and the total input to the system. Figure 6 shows that annual total inputs (precipitation plus irrigation) exceeds annual precipitation by 45% to 86%. Irrigation increased the total input to the system by 662 mm to 1227 mm. The annual increase in drainage due to irrigation is equal to 93% to 100% of the annual irrigation volume (Figure 7). Drainage includes runoff and lateral flow of groundwater which ultimately discharges to surface water. Variation in the drainage often derives from the timing and magnitude of precipitation events. Annual drainage and monthly drainage in wet years trend similarly to precipitation, while monthly drainage in dry years diverges from precipitation patterns when influenced by ET.

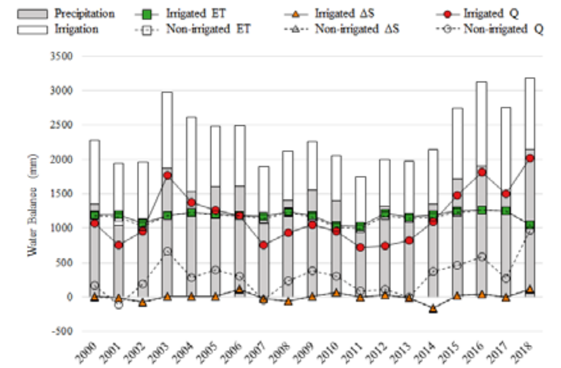

Figure 6. Mean annual water balance under irrigated and non-irrigated conditions across the site.

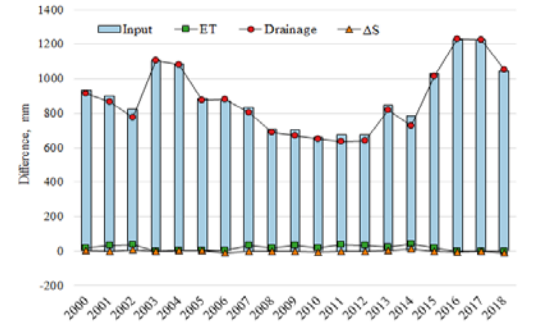

Figure 7. Difference in annual input (precipitation + irrigation), drainage, evapotranspiration (ET) and change in groundwater storage (ΔS) between irrigated and non-irrigated water balances.

Evapotranspiration has a greater influence on the amount of monthly drainage in dry years through its consistent use of available water. At times in dry years, the non-irrigated monthly drainage is negative, which may indicate a change in groundwater storage error. Irrigation increased monthly drainage in dry years by 6 mm to 105 mm, and in wet years by 59 mm to 117 mm (Figure 8). The increase in drainage relative to irrigation volumes ranges from 88% to 119% of monthly irrigation, while in dry years the increase in monthly drainage relative to irrigation ranges from 12% to 158%. Figure 8 shows the contrast between the monthly total input of dry, average and wet years. Not only are the monthly precipitation patterns different, but the irrigation volumes also vary due to FWR management needs to irrigate in order to avoid excessive wastewater volumes in reservoirs.

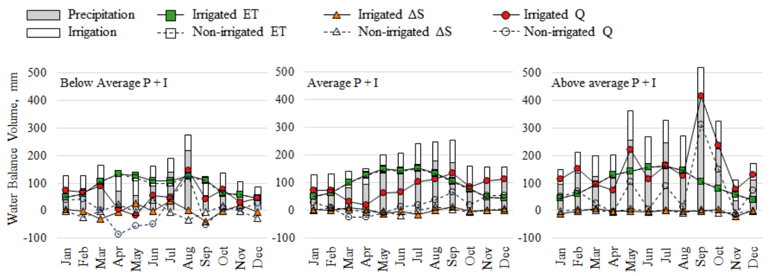

Figure 8. Monthly water balance for below average (one standard deviation below mean precipitation and below mean irrigation, 2002, 2007, 2011), average (2000, 2001, 2004-2006, 2008-2010, 2012-2015, 2017) and above average years (one standard deviation above the mean precipitation and above mean irrigation, 2003, 2016, 2018).

Modelled evapotranspiration (ET) was independent of annual precipitation patterns but dependent on soil water availability and climate conditions (i.e. PET). The stability of ET is consistent in both irrigated and non-irrigation conditions when looking at the site as a whole, with slight increases under the irrigated condition. Irrigation increased overall ET by an average of 18 mm per year. The increases in ET ranged from 0.25 mm to 40 mm. Annual ET to total input (ET/P+I) ratios ranged from 0.40 to 0.62 for irrigated annual ET; ET to precipitation (ET/P) ratios ranged from 0.63 to 1.12 for non-irrigated annual ET. The annual ET ratio tends to be closer to 0.50 with irrigation, indicating increased drainage rather than decreased ET. The annual change in groundwater storage remains close to zero in both irrigated and non-irrigated conditions (Figure

6, Figure 8). The difference in change in groundwater storage due to irrigation ranged from -11 mm to 14 mm annually. Irrigation had little impact on annual patterns of groundwater storage.

Although the impact of irrigation on ET and groundwater storage is minimal on an annual basis, the influence of irrigation on monthly groundwater dynamics (Figure 8) became more pronounced in years with lower annual precipitation. In dry years, monthly groundwater storage was more dynamic and the contrast was more propounded between irrigated and non-irrigated conditions than an average year. The average ET across the site followed expected seasonal trends (Figure 8) with slight reduction of ET during dry summer months when water availability was limited. The monthly ET/P ratio was higher under non-irrigated conditions both in dry (0.56-2.12) and wet years (0.25-1.57) than the ET/(P+I) ratio in dry (0.37-1) and wet years (0.20-0.64). ET rates were stable and interactions between ET, precipitation and infiltration determine water table dynamics and subsequent drainage. Irrigation reduces the impact ET has on the water table by meeting ET demand. High ET rates have a greater influence on the water table in non-irrigated conditions and when precipitation is low.

Although changes in groundwater storage across the site were small over time, the water table increased in some areas due to irrigation. The average water table across the site was slightly higher under irrigated conditions with average water table levels of 6.2 (± 4.1) cm more than non-irrigated conditions. Higher water table levels were observed in well 3 (Figure 9), surrounded by irrigation and in well 6, located in a low topographic area. In these areas, there were larger differences in ET between irrigated and non-irrigated conditions. The greatest difference was in well 3 where ET was 0.9 mm - 305 mm greater under irrigated conditions. Irrigation caused little-to-no change in groundwater levels for wells 1, 11, and 14. In 2010, four new irrigation fields were installed near to groundwater wells 2 and 17. The groundwater levels in these areas varied little between irrigated and non-irrigated conditions until the new fields were installed; after which, higher water tables were observed under irrigated conditions (Figure 10).

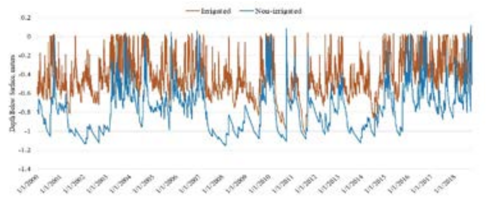

Figure 9. Model simulated depth to groundwater in Well 3 for irrigated and non-irrigated conditions.

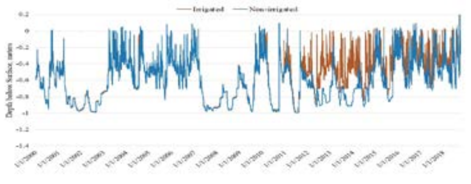

Figure 10. Model simulated depth to groundwater in Well 2 for irrigated and non-irrigated conditions.

3.4 Groundwater Response (ΔS) to Hurricane Florence

Prior studies have observed declines in ET when forests sustain tree damage from hurricanes (Amatya et al 2010). To our knowledge, prior research has not captured groundwater response and recovery for hurricane-impacted forests. On September 14th, 2018, the eye of Hurricane Florence passed 30 miles south-west of the study site. During the two weeks prior to Hurricane Florence's arrival, site managers conducted emergency spraying that exceeded normal hydraulic loading for spray fields. Hurricane Florence delivered 686 mm within two days and raised groundwater elevation to 0.04 – 0.45 meters below ground surface; groundwater elevation on site increased by 0.73 – 1.84 meters (data not shown). Figure 11 shows the relative change in groundwater elevation to the storm event. The non-forested, non-irrigated well 14 changed the least and recovered to a level higher than its pre-hurricane level due to its proximity to the main channel of the creek that flooded to record-levels. For all other wells, groundwater elevation recovered to within 60 – 91% of pre-hurricane depth. Faster recovery occurred in the upper portions of the watershed and at site boundaries while slower recovery was observed for areas with uniform irrigation, flatter topography, and less drainable soils (Figure 11). However, all wells showed groundwater elevation decline even with continued irrigation post Hurricane Florence. The recovery of groundwater levels post Florence provide new insights to forest response and resiliency to extreme hydraulic loading.

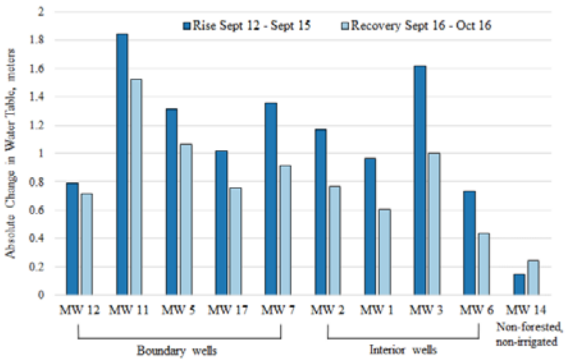

Figure 11. Water level rise and recovery in instrumented wells during and after Hurricane Florence. Wells at the outer boundary of the site recovered to 91% - 65% of pre-hurricane levels, while interior wells recovered to within 60% of pre-hurricane levels.

4 **Discussion**

4.1. Municipal Wastewater Land Application Forests

To our knowledge, this study is the first effort to evaluate how twenty years of municipal wastewater irrigation impacts the water balance of a temperate, coastal forest system. The use of forests to treat municipal wastewater has been in practice since the 1500s and intensively studied and implemented from the 1950s-1990s in the United States (Nichols 2016). During this time, research found that FWR systems removed regulated chemicals to meet permitted requirements (Pennypacker et al 1967) and increased nutrient levels in trees and soils (Stewart et al 1990). There are no studies that examine how forest land treatment systems impact hydrologic change at the watershed scale in relation to water balance dynamics.

This study focused explicitly on water quantity aspects to better understand how post-decadal irrigation influences water balance dynamics that, in turn, impact forest productivity and ecosystem services. This study does not address water quality although water balance quantification is a necessary element towards a comprehensive assessment of waste water treatment practices. Evaluation of hydrological impacts of irrigated forest systems in a lower plain physiographic region are lacking for the southeastern USA. Abrahamson et al (1998) observed that irrigation of *Pinus taeda* had limited impact on forest water use but increased water drainage below 1 meter of the soil surface.

The water balance in non-irrigated coastal forests is dynamic due to the southeastern climate, land forms (wetlands vs uplands), and management regimes (e.g., drained vs non-drained lands) (Sun et al., 2001). Studying water balance dynamics in irrigated forests under varying conditions of water excess provides insight to non-irrigated forest water balances and responses to climate change (Lu et al 2009, Dai et al 2011). In the southeastern USA, climate change will increase the intensity of rainfall events (Webster et al 2014) and sea level intrusion which is another threat to coastal forests (Klepzig et al 2014). Hydrological studies on the impacts of climate variability and sea level rise on forest dynamics are rare for the southeastern USA. The dearth of literature on irrigated forest systems highlights an important research need for coastal forests where extreme events and climate change may increase annual precipitation.

Evapotranspiration, Groundwater and Drainage in the Coastal Plain

In general, coastal plain forest systems are energy-limited and have stable ET due to high water availability (Liu et al 2018; Sun et al 2010, Amatya et al 2016). Drought has limited impact on the ET of young and mature *Pinus taeda* in the coastal plain (Sun et al 2010) due to shallow groundwater availability to trees. Annual ET/P ratios range from 0.55 (wet year) to 1.07 (dry year) (Amatya et al 2016), a value similar to the range of ratios (0.63 to 1.12) simulated in the by MIKE-SHE for non-irrigated, land-applied forest conditions. The high ratios of ET to potential ET were similar to other studies (Amatya et al 2016) and ranged from 0.74 to 0.99 with the lowest ratio occurring in the drought year 2011. The ET simulated in this study was on the high end of annual ET in the coastal plain (Liu et al 2013; Sun et al 2010). Long-term mean annual potential ET in the coastal plain is close to 1140 mm (Amatya et al 2016), which is around 100 mm less than the mean potential ET used for both irrigated and non-irrigated conditions in this study.

This study observed that wastewater irrigation influence is localized to the areas with uniform irrigation sprinklers (Figure 9). However, within these areas, a high water table increased the responsiveness of the groundwater levels to storm events. The water table in the coastal plain was least responsive to rainfall events during the lowest and highest extremes of precipitation. A lower water table reduced water table response to rainfall as well (Gaalen et al 2011). Irrigated plots of *Pinus taeda* also showed less change in storage than non-irrigated plots for sandy soils in North Carolina (Abrahamson et al 1992). Callahan et al (2012) observed that annual change in storage appeared negligible for coastal plain surficial aquifers where recharge to shallow aquifers nearly equals baseflow to surface waters.

The stability of ET and groundwater storage in coastal plain systems makes drainage the most variable component of the water balance for irrigated forest systems. Precipitation drives drainage and potential outflow in forested coastal plains (Harder et al 2007). In this study, both irrigated and non-irrigated drainage followed the pattern of rainfall volume on an annual scale; however, the pattern of drainage was more complex on a monthly scale. Monthly magnitude and timing of drainage followed rainfall patterns in wet years, but drainage patterns were more varied during average and dry years due to interactions between rainfall, irrigation, evapotranspiration, and changes in groundwater storage.

FWR Response to Extreme Rainfall

Climate change is expected to bring more frequent and intense storms, such as Hurricane Florence, to the coastal plain region of North Carolina (Webster et al 2014) where storm response depends on antecedent conditions (Epps et al 2013) and potential outflow is influenced by rainfall amount and temporal distribution (Harder et al 2007). Intense storms destroy trees and, in turn, reduce evapotranspiration which increases drainage (Dai et al 2011). Conversely, climate change is predicted to increase temperatures which would increase the available energy for ET and decrease drainage and streamflow (McNulty et al 2013). In the latter case, particularly during drought conditions, wastewater irrigation becomes important to forest water needs. Coastal forests provide important ecosystem services through storm water mitigation and groundwater recharge (Callahan et al 2017). Intentional storm water and wastewater irrigation to forests could offset negative impacts of climate warming and water shortages for forests.

Results of the MIKE SHE model suggest that monthly ET and change in groundwater storage in a irrigated forest, the FWR, are similar to non-irrigated forests under average rainfall and above-average rainfall years. ET and groundwater storage variability are greater in dry years wherein the irrigated forest responds to drought with increased groundwater consumption and decreased drainage volume. The increase in plant available water from irrigation increases the resilience of the forest to drought. The forest manages dry weather extremes by utilizing available water provisioned by elevated groundwater levels and by ET reduction if available water is limited. Consequently, irrigated forest has high ET and low changes in groundwater storage during wet periods on a monthly basis. Simulated wet periods have high drainage but stable groundwater storage because the site is well-drained. These dynamics show that the saturated FWR system manages intense rainfall events primarily though drainage. The forest has reached its maximum capacity of ET and thus drainage is driven by the amount of irrigation applied to the site.

Conclusions

The goals of this study were to evaluate the impact of irrigation to ET, groundwater, and drainage during twenty years of wastewater treatment at a forest land treatment site. Results suggest that the impacts of irrigation were greatest in areas surrounded by irrigation, with minor impacts to the forest at the perimeter of irrigation fields. Irrigation slightly increased water use by forests across the site particularly in dry years. Increases in ET (up to 12%) during dry times were seen in areas where the water table increased due to irrigation. The fluctuation of the water table varied more with decreasing annual precipitation with few differences between irrigated and non-irrigated conditions in wet and average years. As a result of small changes in ET as a whole, the increase in annual drainage due to irrigation was equal to the volume of irrigation applied. Irrigation was a consistent input to the forest, thus precipitation was the key driver of the variability of drainage.

Coastal forests are groundwater dependent systems that can be vulnerable to extreme events in dry years. Wastewater irrigation for forests reduces this vulnerability by increasing water table elevation and by increasing water availability for ET. In wet years, ET and groundwater levels remain constant while drainage increases in response to rainfall and irrigation. Improved understanding of water balance dynamics can help improve wastewater treatment efficiency at FWR site. Our modeling results suggest that seasonal irrigation volumes can increase earlier than currently practiced to take advantage of higher ET rates in early spring. Studying FWR systems also provides insight to forest response to irrigation and excessive hydraulic loading. These green infrastructure forest systems can provide new insights to the role of forests in managing climate extremes.

Alphabetical list of references

Abrahamson, D. A., Dougherty, P. M., & Zarnoch, S. J. (1998). Hydrological components of a young loblolly pine plantation on a sandy soil with estimates of water use and loss. Water Resources Research, 34(12), 3503–3513. https://doi.org/10.1029/98WR02363

Amatya, D. M., & Trettin, C. C. (2010). Streamflow characteristics of a naturally drained forested watershed in southeast atlantic coastal plain. In ASABE - 9th International Drainage Symposium 2010, Held Jointly with CIGR and CSBE/SCGAB.

Amatya, D. M., & Tian, S. (2016). Long-Term Potential and Actual Evapotranspiration of Two Different Forests on the Atlantic Coastal Plain. Transactions of the ASABE, 59(2), 647–660. https://doi.org/10.13031/trans.59.11141

Birch, A. L., Emanuel, R. E., James, A. L., & Nichols, E. G. (2016). Hydrologic Impacts of Municipal Wastewater Irrigation to a Temperate Forest Watershed. Journal of Environment Quality, 45(4), 1303. https://doi.org/10.2134/jeq2015.11.0577

Callahan, T. J., Amatya, D. M., & Stone, P. A. (2017). Coastal forests and groundwater: Using case studies to understand the effects of drivers and stressors for resource management. Sustainability (Switzerland), 9(3). https://doi.org/10.3390/su9030447

Callahan, T. J., Vulava, V. M., Passarello, M. C., & Garrett, C. G. (2012). Estimating groundwater recharge in lowland watersheds. Hydrological Processes, 26(19), 2845–2855. https://doi.org/10.1002/hyp.8356

Dai, Z., Amatya, D. M., Sun, G., Trettin, C. C., Li, C., & Li, H. (2011). Climate variability and its impact on forest hydrology on South Carolina coastal plain, USA. Atmosphere, 2(3), 330-357. https://doi.org/10.3390/atmos2030330

Epps, T. H., Hitchcock, D. R., Jayakaran, A. D., Loflin, D. R., Williams, T. M., & Amatya, D. M. (2013). Characterization of Storm Flow Dynamics of Headwater Streams in the South Carolina Lower Coastal Plain. Journal of the American Water Resources Association, 49(1), 76–89. https://doi.org/10.1111/jawr.12000

Guinn Garrett, C., Vulava, V. M., Callahan, T. J., & Jones, M. L. (2012). Groundwater-surface water interactions in a lowland watershed: Source contribution to stream flow. Hydrological Processes, 26(21), 3195–3206. https://doi.org/10.1002/hyp.8257

Harder, S. V., Amatya, D. M., Callahan, T. J., Trettin, C. C., & Hakkila, J. (2007). Hydrology and water budget for a forested Atlantic Coastal Plain watershed, South Carolina. Journal of the American Water Resources Association, 43(3), 563–575. https://doi.org/10.1111/j.1752-1688.2007.00035.x

Klepzig, K., Shelfer, R., & Choice, Z. (2014). Outlook for Coastal Plain forests: a subregional report from the Southern Forest Futures Project. General Technical Report - Southern Research

Station, USDA Forest Service; 2014. (SRS-196):Xi + 68 Pp. Many Ref. Retrieved from http://www.srs.fs.usda.gov/pubs/gtr/gtr_srs196.pdf http://oxfordsfx.hosted.exlibrisgroup.com/oxford?sid=OVID:cabadb&id=pmid:&id=doi:&issn=&isbn=&volume=&issue=SRS-19

La Torre Torres, I. B., Amatya, D. M., Sun, G., & Callahan, T. J. (2011). Seasonal rainfall-runoff relationships in a lowland forested watershed in the southeastern USA. Hydrological Processes, 25(13), 2032–2045. https://doi.org/10.1002/hyp.7955

Liu, X., Sun, G., Mitra, B., Noormets, A., Gavazzi, M. J., Domec, J. C., McNulty, S. G. (2018). Drought and thinning have limited impacts on evapotranspiration in a managed pineplantation on the southeastern United States coastal plain. Agricultural and Forest Meteorology, 262(March), 14–23. https://doi.org/10.1016/j.agrformet.2018.06.025

Lu, J., Sun, G., McNulty, S. G., & Comerford, N. B. (2009). Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. Wetlands, 29(3), 826–836. https://doi.org/10.1672/07-162.1

Manda, A. K., & Klein, W. A. (2014). Rescusing degrading aquifers in the Central Coastal Plain of North Carolina (USA): Just process, effective groundwater management policy, and sustainable aquifers, 1943–1959. https://doi.org/10.1002/2013WR014222.Received

McEachran, A. D., Hedgespeth, M. L., Newton, S. R., McMahen, R., Strynar, M., Shea, D., & Nichols, E. G. (2018). Comparison of emerging contaminants in receiving waters downstream of a conventional wastewater treatment plant and a forest-water reuse system. Environmental Science and Pollution Research, 25(13), 12451–12463. https://doi.org/10.1007/s11356-018-1505-5

Mcnulty, S., Caldwell, P., Doyle, T. W., Johnsen, K., Liu, Y., Mohan, J., & Prestemon, J. (2013). Forests and Climate Change in the Southeast USA Contributing Authors, 165–189. Retrieved from https://www.srs.fs.usda.gov/pubs/ja/2013/ja_2013_mcnulty_001.pdf

MIKE SHE users's manual Volume 1, DHI Technologies (2017)

Muga, H., and J. Mihelcic. 2008. Sustainability of wastewater treatment technologies. Journal of Environmental Management. 88:437-447. Doi:10.1016/j.jenvman.2007.03.008

Nichols, E. G. (2016). Current and future opportunities for forest land application systems of wastewater. In Phytoremediation: Management of Environmental Contaminants, Volume 4. https://doi.org/10.1007/978-3-319-41811-7_9

Pennypacker, S. P., Sopper, W. E., & Kardos, L. T. (1967). Renovation of Wastewater Effluent by Irrigation of Forest Land. Source Journal (Water Pollution Control Federation), 39(2), 285–296. Retrieved from http://www.jstor.org/stable/25035743%0Ahttp://about.jstor.org/terms

Stewart, H. T. L., Hopmans, P., Flinn, D. W., & Hillman, T. J. (1990). Nutrient accumulation in trees and soil following irrigation with municipal effluent in Australia. Environmental Pollution, 63(2), 155–177. https://doi.org/10.1016/0269-7491(90)90065-K

Sun, G., Mcnulty, S. G., Shepard, J. P., Amatya, D. M., Riekerk, H., Comerford, N. B., Swift, L. (2001). Effects of timber management on the hydrology of wetland forests in the southern United States, 143.

Sun, G., Noormets, A., Gavazzi, M. J., McNulty, S. G., Chen, J., Domec, J. C., … Skaggs, R. W. (2010). Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA. Forest Ecology and Management, 259(7), 1299–1310. https://doi.org/10.1016/j.foreco.2009.09.016

Van Gaalen, J. F., Kruse, S., Lafrenz, W. B., & Burroughs, S. M. (2013). Predicting Water Table Response to Rainfall Events, Central Florida. GroundWater, 51(3), 350–362. https://doi.org/10.1111/j.1745-6584.2012.00970.x

Webster, P. J., Holland, G. J., & Curry, J. A. (2014). Changes in Tropical Cyclone Number , Duration , and Intensity in a Warming Environment Author (s): P . J . Webster , G . J . Holland , J . A . Curry and H . -R . Chang. Science, 309(5742), 1844–1846. https://doi.org/10.1111/j.0033-0124.1951.006_a.x

Zhang, J., & Ross, M. (2015). Comparison of IHM and MIKE SHE Model Performance for Modeling Hydrologic Dynamics in Shallow Water Table Settings. Vadose Zone Journal, 14(7), 0. https://doi.org/10.2136/vzj2014.03.0023.

Appendix

Gibson, N.E.[1] , Sun, G.[2] , Nichols, E.G.[3] **Impacts of Municipal Wastewater Irrigation to the Water Balance in a Forested Water Reuse System**. *Ecohydrology. In Review.*

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. March 21, 2019. Impacts of Irrigated Municipal Wastewater to the Water Balance in a Forested Water Reuse System. Unpublished Master's Thesis.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. March 21, 2019. Impacts of Irrigated Municipal Wastewater to the Water Balance in a Forested Water Reuse System. Session Presentation: *NC Water Resources Research Institute Annual Conference,* Raleigh, NC, USA.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. March 20, 2019. Impacts of Irrigated Municipal Wastewater to the Water Balance in a Forested Water Reuse System. Presentation: *City of Jacksonville Wastewater Treatment Facility,* Jacksonville, NC, USA.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. January 14, 2019. Impacts of Irrigated Municipal Wastewater to the Water Balance in a Forested Water Reuse System. Presentation: *City of Jacksonville Community Center,* Jacksonville, NC, USA.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. November 5, 2018. A MIKE SHE Model to Understand Water Balance Dynamics at a Forested Municipal Land Treatment Site. Session Presentation: *American Water Resources Association Annual Conference,* Baltimore, MD, USA.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. October 3, 2018. A Watershed Model to Understand Water Balance Dynamics and Support Sewer Utility Resilience at the Jacksonville NC Forest Water Re-Use Facility. Poster Presentation: *Water Smart Innovations Annual Conference,* Las Vegas, NV, USA.

Gibson, N.E., Sun, G., Nichols, E.G., Martin, K. March 14, 2018. A Watershed Model to Understand Water Balance Dynamics and Support Sewer Utility Resilience at the Jacksonville NC Forest Water Re-Use Facility. Poster Presentation: *NC Water Resources Research Institute Annual Conference,* Raleigh, NC, USA.