Title: Geographically Isolated Wetlands and Watershed Hydrology: A Modified Model Analysis

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Abstract

Geographically isolated wetlands (GIWs) are defined as wetlands that are completely surrounded by uplands. While GIWs are therefore spatially isolated, field-based studies have observed a continuum of hydrologic connections between these systems and other surface waters. Yet few studies have quantified the watershed-scale aggregate effects of GIWs on downstream hydrology. Further, existing modeling approaches to evaluate GIW effects at a watershed scale have utilized conceptual or spatially disaggregated wetland representations. Working towards wetland model representations that use spatially explicit approaches may improve current scientific understanding concerning GIW effects on the downstream hydrograph. The objective of this study was to quantify the watershed-scale aggregate effects of GIWs on downstream hydrology while emphasizing a spatially explicit representation of GIWs and GIW connectivity relationships. We constructed a hydrologic model for a ~202 km² watershed in the Coastal Plain of North Carolina, USA, a watershed with a substantial population of GIWs, using the Soil and Water Assessment Tool (SWAT). We applied a novel representation of GIWs within the model, facilitated by an alternative hydrologic response unit (HRU) definition and modifications to the SWAT source code that extend the model's "pothole" representation. We then executed a series of scenarios to assess the downstream hydrologic effect of various distributions of GIWs within the watershed. Results suggest that: (1) GIWs have seasonally dependent effects on baseflow; (2) GIWs mitigate peak flows; and (3) The presence of GIWs on the landscape impacts the watershed water balance. This work demonstrates a means of GIW simulation with improved spatial detail while showing that GIWs, in-aggregate, have a substantial effect on downstream hydrology in the studied watershed.

1. Introduction

“Geographically isolated” wetlands (GIWs) are wetland systems typically surrounded by uplands. These systems characteristically have limited or unobservable surface hydrologic connections with other surface water bodies (Tiner, 2003; Winter, 2003). GIWs support an array of ecological processes including surface water storage and recharge (Pomeroy *et al.*, 2014), watershed biogeochemical cycling (Creed *et al.*, 2003), and biodiversity (Leibowitz and Nadeau, 2003). Despite these benefits, approximately 30-90% of the spatial extent of global wetlands – including GIWs and wetlands in general – has been lost to anthropogenic activities (Junk *et al.*, 2013). Further, regulatory protection for these systems has been challenged within the United States. A ruling from a 2001 US Supreme Court case, the Solid Waste Agency of Northern Cook County (SWANCC) vs. US Army Corps of Engineers (531 US 159 2001) held that “isolated,” intrastate, non-navigable waters could not be regulated under the Clean Water Act as “waters of the United States” based solely on the presence of migratory birds (Downing *et al.*, 2003). The subsequent Rapanos vs. US Army Corps of Engineers ruling (“Rapanos,” 547 US 715 2006) determined that protection for these systems would be afforded only if the waters significantly affect, either alone or in combination with similarly situated waters, navigable-in-fact waters – waters for which regulatory protections are undisputed. These decisions, the loss of wetlands globally, and limited watershed-scale studies on GIW systems, have led to a substantial research need for methods capable of quantifying the magnitude, extent, and duration of GIW connections with downstream waters. A step toward addressing these key questions involves quantifying the potential aggregate effects of GIWs on downstream hydrographs.

Our understanding of GIWs and the processes governing their connective relationships with downstream surface waters are informed, in part, by previous work examining the

hydrologic effects of wetlands in general (e.g., Vining, 2002; Bullock and Acreman, 2003; Quinton *et al.*, 2003; Acreman and Holden, 2013). However, few studies have provided targeted evaluations of the effects of GIWs on downstream hydrology (but see, as examples, Leibowitz and Vining, 2003; Wang *et al.*, 2008; Viger *et al.*, 2010; Almendinger *et al.*, 2011; Wilcox *et al.*, 2011; McLaughlin *et al.*, 2014; Pomeroy *et al.*, 2014). Models using available long-term data – or supplementing current understanding in the absence of such abundant data – are important tools in quantifying aggregate GIW hydrologic effects. Watershed-scale simulation models show clear potential to quantify these effects due to their explicit representation of hydrologic and hydraulic dynamics (Golden *et al.*, 2014).

A limited number of mechanistic modeling-based studies have provided important assessments of the influence of GIWs and/or landscape depressions on watershed-scale hydrologic processes, primarily using conceptual landscapes and/or lumped parameter modeling approaches. McLaughlin *et al.* (2014), for example, depicted GIWs within an idealized landscape by coupling soil moisture, upland water table, and wetland stage models. They found that increasing total wetland area and decreasing individual wetland size decreased landscape water table variation. Further, the number of wetlands within the landscape was shown to significantly affect wetland-groundwater interactions. Pomeroy *et al.* (2010) and Pomeroy *et al.* (2014) utilized the Prairie Hydrological Model (PHM), a modified version of the Cold Regions Hydrological Model (Pomeroy *et al.*, 2007), to simulate the hydrologic influence of prairie pothole depressions within the Canadian plains. Pomeroy *et al.* (2014) incorporated a conceptual, network-based model of synthetic wetlands parameterized via the separate physically-based Wetland Digital Elevation Model Ponding Model (Shook *et al.*, 2013; Pomeroy *et al.*, 2014). Pomeroy *et al.* (2014) demonstrated that removal of all simulated depressions within the PHM

resulted in a 55% increase in total flow volumes throughout their simulation period. Additionally, Vining (2002) utilized the Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1995) to simulate prairie pothole depressions within the Starkweather Coulee basin, North Dakota, USA. The PRMS model depicts closed basin depressional storage via an aggregate representation of all depressional storage within a simulated hydrologic response unit (HRU) where a constant proportion of HRU uplands drains to the depression reservoir (Vining, 2002; Viger *et al.*, 2010). Vining (2002) simulated a 49% decrease in streamflow by increasing the quantity of closed-basin depressional area within the utilized PRMS model. Viger *et al.* (2010) similarly applied PRMS in the Upper Flint River basin, Georgia, USA and determined that wetlands decrease daily streamflow values for all but the lowest of streamflow values.

Additional studies have evaluated the watershed-scale hydrologic effects of GIWs and/or landscape depressions using the Soil and Water Assessment Tool (SWAT), a widely-utilized hydrologic model (Neitsch *et al.*, 2009; Gassman *et al.*, 2014). Almendinger *et al.* (2011), for example, applied SWAT to examine the influence of closed-basin depressional areas upon hydrologic flows and sediment yields in the Willow River watershed, Wisconsin, USA and Sunrise River, Minnesota, USA. Almendinger *et al.* (2011) characterized wetlands at the subbasin scale using the model's wetland and pond representations. SWAT subbasins are composed of a series of HRUs simulated as de-spatialized entities such that a constant, uniform fraction of each HRU is routed to the wetland or pond reservoir. Wang *et al.* (2008) designed and tested a "hydrologic equivalent wetland" (HEW) representation for SWAT to evaluate wetland hydrologic functions within the Otter Trail River Watershed in Minnesota, USA. A HEW is defined using calibrated parameters that describe the aggregate functional attributes of wetlands at the subbasin-scale. Wang *et al.* (2008) determined that, compared to a SWAT model with no

wetland representation, HEW-model simulations had substantially decreased probabilities of streamflow exceedance, particularly for higher streamflow values. Other SWAT applications have utilized the model's "pothole" representation and found that the inclusion of depressional areas in simulations improves model performance in landscapes dominated by these systems, such as in the Midwestern Corn Belt, USA, and the Northern lowlands of Germany (Du *et al.*, 2005; Du *et al.*, 2006; Kiesel *et al.*, 2010). The pothole representation of wetlands provides improved spatial resolution in SWAT because it is simulated at the HRU-scale (compared to alternative subbasin-scale wetland representations) yet is nonetheless limited by the lumped parameterization and processing of HRUs within the model. These studies provide useful insights to the hydrologic effects of GIWs at broad spatial scales using conceptual or spatially-aggregated GIW representations. The development of spatially explicit representations of GIWs and their downstream connectivity dynamics is a particularly important research direction that capitalizes on these previous efforts to advance our understanding of GIWs and their hydrological effects. Furthermore, such critical work is needed in Coastal Plain watersheds, and indeed other areas with abundant wetland resources, as only limited studies on GIW connectivity and downstream hydrological effects have occurred yet abundant GIWs and GIW complexes exist (e.g., Golden *et al.*, 2015).

The objective of this study was to assess the aggregate hydrologic effects of GIWs on downstream hydrology in a Coastal Plain watershed of the Southeastern United States. We placed particular emphasis on developing a more spatially explicit representation of GIWs and GIW-watershed connectivity relationships while quantifying these effects. We satisfied our objective via a twofold approach. Firstly, we constructed a SWAT model to represent a ~202 km² drainage basin in the Nahunta Watershed, North Carolina, USA. We modified the

representation of GIWs within the SWAT model to incorporate additional spatial detail in depiction of GIWs and GIW connectivity relationships. The modified SWAT model: (1) Explicitly incorporated a spatial data layer of the basin's GIWs to apply an alternative HRU definition; and (2) Allowed for subsurface inflow routing to our modified GIW representations as an extension of the SWAT model's "pothole" representation. We then calibrated the modified SWAT model to USGS streamflow observations at the watershed outlet. The modified and calibrated SWAT model constituted our "Baseline model." Secondly, we executed a series of scenarios that removed all or sub-sets of GIWs from the Baseline model to assess changes in watershed water balances and the downstream hydrograph relative to the Baseline simulation. Our approach and results advances current scientific understanding of the watershed-scale hydrologic impacts of GIWs and demonstrates a more spatially explicit representation of GIWs in models for future GIW-based hydrologic research in other watersheds and systems.

2. Methods

2.1. Study Area and Wetland Identification

The study area watershed was delineated by United States Geological Survey (USGS) station #02091000 at Nahunta Swamp near Shine, North Carolina, USA (Figure 1A). The Nahunta watershed covered approximately 202 km² and was dominated by agriculture (55%), forest (14%), and wetlands (16%)(Fry *et al.*, 2011). Precipitation observations at a weather gauge approximately 1.4 km south of the watershed boundary indicated an average annual precipitation of 120.2 cm (± 18.8 cm); an average monthly precipitation of 10.0 cm (± 6.3 cm); and an average daily precipitation of 0.33 cm (± 0.96 cm) for the period 1990 through 2010 (NCDC, 2011). Daily high temperatures averaged 22.1 °C (± 8.8 °C) with a maximum of 40.0 °C and daily low temperatures averaged 9.7 °C (± 8.8 °C) with a minimum of -15.6 °C for the period 1990 through

2010 (NCDC, 2011). The elevation ranged from 74.6 m in the western boundary of the basin to a low of 15.7 m at the USGS station (Gesh *et al.*, 2007). Study area soils were generally porous and dominated by the Norfolk, Coxville, and Rains series composed of loamy sand, sandy loams, and loam textures at the top soil horizon that are underlain by clay loams, sandy clays, and fine sandy loams (USDA-ARS, 2013). Saturated hydraulic conductivity values of the series ranged between 15.22 mm hr⁻¹ to 508.1 mm hr⁻¹ in the upper soil horizon and 5.08 mm hr⁻¹ to 50.8 mm hr⁻¹ below (Schwarz and Alexander, 1995). The subsurface below upland flats in the watershed had a confining unit at approximately 7 to 8 m below the surface (Spruill *et al.*, 2004).

The North Carolina Coastal Region Evaluation of Wetland Significance (NC-CREWS) (Sutter *et al.*, 1999), an updated version of the US National Wetlands Inventory (NWI), identified approximately 22.1 km² of wetlands within the Nahunta watershed (see Figure 1B). Dominant wetland types, according to the NC-CREWS, include bottomland hardwood wetlands, pineland wetlands, riverine swamp forests, depressional swamp forests, and hardwood and pine flats. Regional GIWs have been characterized as Carolina Bays and ephemeral wetlands that may be completely dry during periods of low precipitation (Sharitz, 2003). Regional GIWs have also been characterized as “flow through” systems that receive groundwater from adjacent uplands while recharging groundwater in lower topographic areas (Sun *et al.*, 2006; Pyzoha *et al.*, 2008). Outflow via overland spillage is characterized in Coastal Plain landscapes to typically occur only during or following extreme events (e.g., summer convective storms, hurricanes) (Sharitz, 2003).”

We identified GIWs within the study area using a methodology developed by Lane *et al.* (2012) using NC-CREWS (Sutter *et al.*, 1999). All NC-CREWS delineated wetland polygons intersecting a 10-meter buffer (20-meter total buffer cross-width) of the National Hydrography

Dataset (NHD) stream network were identified as non-GIW s or “connected” waters. The buffer included NHD flow lines and stream areas but excluded NHD water bodies smaller than 20 ha to ensure that potential GIW s were not inadvertently removed from the analysis. Approximately 14.9 km² of NC-CREWS wetlands were identified as “connected.” Wetlands that did not intersect the NHD-buffer were considered putative GIW s (for additional information on methods, see Lane *et al.*, 2012). A total of 280 GIW s, comprising an area of 7.21 km² (or ~3.6% of the study area extent and 33% of all study area wetlands) were identified using this method. The storage capacities of these GIW s (Figure 2) were estimated following the three-step process of Lane and D'Amico (2010): (1) The average elevation of each GIW was estimated by converting each GIW feature boundary to a series of vertices and then extracting the elevation for each vertex using the digital terrain model; (2) The average feature vertex elevation for each GIW feature was taken as the GIW's maximum stage-height; and (3) Elevation estimates were input into an GIS geoprocessing tool which provided GIW volume estimates (specifically the *Polygon Volume* tool within the *3D Analyst Toolbox*; ESRI, Redlands CA, ArcGIS v 10.2). This method of estimating GIW storage capacities does not account for errors attributable to standing water (data voids) within a GIW at the time of Lidar data collection. Data voids are one of the most observable errors in Lidar data (Shrestha *et al.*, 2003).

2.2. Hydrologic Model

We utilized SWAT to evaluate the effects of GIW s on downstream hydrology. SWAT is a widely-utilized watershed scale hydrologic model previously applied to evaluate landscape depressions and/or potential GIW s as impacting watershed hydrologic processes (e.g., Wang *et al.*, 2008; Almendinger *et al.*, 2011). The model is semi-distributed, semi-physically-based and operates on hourly, daily or monthly time steps. The model represents landscapes as a series of

subbasins where each subbasin is partitioned into an array of HRUs. HRUs are notably de-spatialized such that an HRU may show a disconnected spatial pattern yet be simulated as a singular entity within the model. As a given quantity of precipitation falls upon each HRU, surface runoff and groundwater processes are simulated and a portion of the HRU water balance is routed to the subbasin reach (i.e., the subbasin's portion of the greater stream network). When hydrologic simulations are completed for all HRUs within a subbasin (here at a daily time step), in-stream hydrologic processes are simulated for the subbasin reach as flow is routed progressively downstream. The model relies upon the US Department of Agriculture Soil Conservation Service curve number (CN) method to estimate surface runoff. Detailed descriptions of the model and simulated processes are provided by Neitsch *et al.* (2009) and Neitsch *et al.* (2012).

The Nahunta SWAT model was constructed using a 30-meter digital elevation model (DEM) (Gesh *et al.*, 2007); the 2006 National Land Cover Dataset (NLCD) (Fry *et al.*, 2011); and the State Soil Geographic (STATSGO) Database (Schwarz and Alexander, 1995). These spatial data sets served as input into ArcSWAT (Ver. 2009.93.7b) to delineate 47 subbasins with an approximate mean area of 4.27 km² ($\pm$ 2.75 km²). The model uses daily precipitation and temperature observations obtained from a National Climatic Data Center (NCDC, 2011) gauge station approximately 1.4 km south of the watershed at Goldsboro Seymour Johnson Air Force Base, North Carolina, USA (35.46°N, 77.96°W).

2.3. Wetland Representations

The SWAT model provides three modes of wetland representation. The “wetland” (hereafter referred to as the “conventional wetland”), and “pond” representations are the traditional means of wetland simulation (e.g., Wu and A. Johnston, 2008; Babbar-Sebens, 2012;

Martinez-Martinez *et al.*, 2014). The conventional wetland and pond representations have also been applied in parallel to depict structurally and functionally distinct systems (see Almendinger *et al.*, 2011). The conventional wetland and pond representations differ in that additional management options are available to the pond representation though these options are not discussed here (see Neitsch *et al.*, 2009). The conventional wetland and pond representations are simulated once each per subbasin such that all wetlands within a subbasin are depicted via these aggregated or “lumped” representations (i.e., wetland parameters with subbasins with > 1 wetland are aggregated). The water balance equations associated with the conventional wetland and pond are depicted within Eq. 1 and 2, respectively,

$$V_w = V_{w,st} + V_{w,in} - V_{w,out} + V_{w,pcp} - V_{w,et} - V_{w,sp} \quad (\text{Eq. 1})$$

$$V_{pd} = V_{pd,st} + V_{pd,in} - V_{pd,out} + V_{pd,pcp} - V_{pd,et} - V_{pd,sp} \quad (\text{Eq. 2})$$

where V_w is the volume of water (m^3) existing within the conventional wetland at the end of a given time-step, V_{pd} is the volume of water (m^3) existing within the pond at the end of a given time-step, V_{st} is the volume of water (m^3) existing within the entity at the beginning of a time-step, V_{in} is the volume of water (m^3) flowing into the entity via overland flow during the time-step, V_{out} is the volume of water (m^3) exiting the entity during the time-step, V_{pcp} is the volume of water (m^3) entering the entity as precipitation during the time-step, V_{et} is the volume of water (m^3) exiting the wetland via evaporation during the time-step, and V_{sp} is the volume of water (m^3) exiting the entity via seepage during the time-step. The equations describing the calculation of these parameters are reviewed in detail by Neitsch *et al.* (2009).

The “pothole” representation presents a third means of wetland depiction within SWAT. The pothole representation is intended as a method to simulate closed depressional areas typical of low relief and geologically young landscapes (Neitsch *et al.*, 2009). As such, the pothole

representation has been used to depict depressional storage areas such as the relatively recently glaciated prairie pothole region of Canada and the United States (see Du *et al.*, 2005). The pothole water balance equation is depicted as Eq. 3:

$$V_{pt} = V_{pt,st} + V_{pt,in} - V_{pt,out} + V_{pt,pcp} - V_{pt,et} - V_{pt,sp} \quad (\text{Eq. 3})$$

where V_{pt} represents the volume of water (m^3) existing within the pothole at the end of a given time-step. The equations that calculate parameters in Eq. 3 are described by Neitsch *et al.* (2009). Unlike the conventional wetland and pond representations, potholes are simulated at the HRU scale such that pothole inflow, $V_{pt,in}$, is a function of the out-flow from a singular HRU or subset of HRUs within the same subbasin, depending upon the utilized model version. Earlier versions of SWAT (approximately Rev. 491 and earlier) allow a singular pothole per subbasin and permit the model user to route flow from multiple HRUs within a subbasin to the pothole within that subbasin. The quantity of seepage from a pothole, $V_{pt,sp}$, is dictated by the saturated hydraulic conductivity parameter of the top soil horizon of the HRU within which the pothole is placed. This quantity, $V_{pt,sp}$, represents the sole means by which water can exit the pothole reservoir via the subsurface; therefore, this single parameter effectively governs both the vertical and lateral seepage from the pothole representation. Thus, pothole seepage, $V_{pt,sp}$, depicts the aggregate quantity of vertical and lateral seepage from the pothole reservoir.

2.4. Existing GIW Representation Limitations

As applied to the hydrologic characterization of GIW's, the conventional wetland, pond and pothole representations have certain limitations. The conventional wetland and pond representations cannot receive inflow solely from specific HRUs or even specific sub-sections of a subbasin known to drain to a GIW. Rather, a constant portion of outflow from all HRUs within the subbasin must be routed to the conventional wetland or pond representations. This is a

consequence of their simulation at the subbasin-scale and that all HRUs within a subbasin are de-spatialized. Thus, inflow, expressed as $V_{w,in}$ and $V_{pd,in}$ in Eq. 1 and 2, respectively, is calculated as a function of the lumped sum of overland flow from all HRUs within the subbasin. Further, the pothole representation will inaccurately depict GIW spatial and hydrologic relationships where HRU boundaries do not conform to the boundaries of a GIW and its upgradient drainage area. This limitation arises for two reasons. First, the pothole representation, while simulated at the HRU-scale, must conform to the spatial and hydrologic relationships dictated by the HRU within which it is placed. Thus, a pothole placed within a HRU that has a disaggregated (i.e. disconnected) spatial pattern across the subbasin is likewise represented. Second, HRUs made to drain to a pothole HRU may also be spatially disaggregated throughout the subbasin – assuming use of the earlier pothole representation (approximately Rev. 492 and earlier). Thus, inflow to a pothole ($V_{pt,in}$) is necessarily drawn from outside the actual upgradient GIW drainage area in cases where a HRU draining to the pothole extends beyond the drainage area boundary.

Furthermore, the pothole representation has limitations in depicting subsurface inflow to GIWs within landscape dominated by porous soils and subsurface flows. Pothole inflow, $V_{pt,in}$, is calculated solely as a function of HRU surface outflow. Thus, the quantity of water entering the pothole HRU's reservoir during a given time period (e.g., day), expressed as the parameter $V_{pt,in}$ in Eq. 3, is calculated as described within Eq. 4:

$$V_{pt,in} = \sum_{j=1}^{j=hrutot} (qday_j * potfr_j) \quad (\text{Eq. 4})$$

where j is a HRU index, $hrutot$ represents the total number of HRUs within a subbasin, $qday$ is the surface contribution (via surface runoff from precipitation) to the subbasin reach for the given day (mm), and $potfr$ is the fraction of the HRU draining to the pothole HRU. Subsurface outflow from HRUs draining to the pothole representation are therefore ignored. The lack of

subsurface inflow to the pothole representation is, in part, a presumed artifact of its original intended use - simulation of prairie potholes within regions of Canada and the United States (see Du *et al.*, 2005). Yet subsurface transport is an important component of GIW hydrology in landscapes dominated by highly porous soils and subsurface flow (Winter, 2003; Pyzoha *et al.*, 2008). Thus, the pothole representation, as-is, insufficiently depicts GIW hydrologic processes within certain landscapes.

2.5. Model Revisions

We executed a series of revisions to correct for two key limitations of the SWAT model's pothole representation. The first revision concerned the pothole representation's characterization of GIW and GIW drainage area boundaries that impact hydrologic transport within the model's subbasins. We executed a new method of defining HRUs to force HRU boundaries to conform to GIWs and GIW drainage area boundaries and developed Python (v. 2.7) scripts to conduct these modifications. We redefined HRUs as unique combinations of land use, soil, and slope, and developed a fourth attribute that serves as an indicator of the HRU's spatial and hydrologic relationship to identified GIWs. The fourth attribute indicated (1) The HRUs existence within a GIW boundary, (2) The HRUs existence within a GIW's drainage area, or (3) The HRUs existence outside of any GIW and GIW drainage area. Following the redefinition of HRUs in this manner, all HRUs identified as existing within GIW-identified boundaries were dissolved into a singular pothole HRU. A pothole was placed within the pothole HRU with a maximum storage capacity equivalent to that calculated for the corresponding NC-CREWS GIW feature(s). All HRUs identified as existing within the GIW drainage area were made to drain to the newly created pothole HRU (Figure 3). We assume a static surface area for each pothole reservoir

equivalent to the pothole HRU's surface area. Additional information regarding our modification of HRU boundaries is provided within the Supplementary Material.

The second model revision was intended to correct for the inability of SWAT to represent subsurface inflow to potholes, an important component of GIW hydrology in landscapes dominated by porous soils and subsurface flow (Pyzoha *et al.*, 2008). We applied a series of modifications to the model's FORTRAN source code for HRUs that drain to pothole HRUs. The original SWAT source code (Rev 488) dictated that overland flows for a time period and from any HRU draining to a pothole were routed to the pothole HRU's reservoir (Eq 4). We modified Eq 4 for our analyses such that the HRU draining to the pothole directed all of the HRU's daily water yield to the pothole HRU. Thus, Eq 4 was modified to Eq 5:

$$V_{pt,in} = \sum_{j=1}^{j=hrutot} ((qday_j + latq_j + gwq_j) * potfr_j) \quad (\text{Eq. 5})$$

where j is a HRU index, $latq$ is the soil profile flow contribution to the subbasin reach (mm), and gwq is the shallow aquifer flow contribution to the subbasin reach (mm). Our coded changes replicate the inflow dynamics of the conventional wetland and pond representations; inflow for those representations ($V_{w,in}$ and $V_{pd,in}$ in Eq 1 and 2 respectively) are also calculated as a function of the $qday_j$, $latq_j$, and gwq_j parameters. Additional information regarding our modification of the SWAT FORTRAN source code files is provided within the Supplementary Material. Our model revisions collectively produce an improved depiction of the hydrologic relationships between GIWs and the greater watershed (Figure 4).

2.6. Model Calibration and System Representation

We calibrated the revised SWAT model incorporating the GIW representations using average daily streamflow records for USGS station #02091000 at Nahunta Swamp near Shine, North Carolina. We employed a model warm-up period of three calendar years (1998-2000) and

a calibration period of four calendar years (2001-2004). Average annual precipitation was 112.9 cm for the calibration period (minimum = 93.61 cm in 2001; maximum = 141.68 cm in 2003). We used the Sequential Uncertainty Fitting ver. 2 (SUFI-2) routine and the parallel processing module within the SWAT Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour *et al.*, 2007; Rouholahnejad *et al.*, 2012) for all calibration runs. We elected to utilize the Nash-Sutcliffe Efficiency (NSE) metric (Nash and Sutcliffe, 1970) as a means of evaluating alternative parameter sets within the SUFI-2 routine. The NSE squares the difference between simulated and observed flows to emphasize peak flows during calibration (Legates and McCabe, 1999; Price *et al.*, 2012). The SUFI-2 procedure utilizes a Latin Hypercube Sampling (LHS) procedure to parameterize model runs and ensure an efficient exploration of the parameter space.

We executed an initial SUFI-2 run of 500 iterations with 19 SWAT parameters to serve as a preliminary global sensitivity analysis (Table 1). These SWAT parameters were included to maintain a diverse selection of parameters that impact simulated groundwater, soil, runoff, evaporation, geomorphologic, and channel processes as suggested by van Griensvan *et al.* (2006). The initial SUFI-2 run identified six parameters as statistically significant ($p < 0.05$; Table 1). These sensitive parameters were included within a second calibration run along with the channel Manning's N (CH-N2) and hydraulic conductivity (CH-K2) parameters. The CH-N2 and CH-K2 parameters were not statistically significant in the initial 500 runs but were included in the second calibration to compensate for uncertainties associated with the limited riparian wetland process representations in SWAT and channelization of the Nahunta watershed's primary reach, Shine Creek (see Section 5 for further discussion). The second SUFI-2 run of 2000 iterations resulted in a parameter set with a daily NSE value of 0.66, a ratio of the root mean square error to the standard deviation (RSR) value of 0.58 and a percent bias (PBIAS)

value of -10.8 (Figure 5). NSE values above 0.50, RSR values below 0.70, and PBIAS values less than ± 25.0 are considered satisfactory at a monthly time-step with the understanding that more forgiving performance thresholds are warranted at finer resolution time-steps (e.g., daily, sub-daily) (Moriiasi *et al.*, 2007). Our revised and calibrated model (the heretofore described “Baseline” model), executed at a daily time-step (2001-2004), therefore exceeded stricter monthly performance criteria.

We evaluated the selected parameter set for the Baseline model by focusing on the extent to which it represents hydrologic processes within the watershed. We emphasize the rationale for our evaluation with respect to three parameters in-particular. The calibrated SOL-K, RCHR-DP, and GWQMN parameters (Table 1) impact the Baseline model’s representation of subsurface hydrologic processes. SWAT (SWAT2009 Rev. 488) represents the subsurface of each HRU in three parts: (1) A soil profile; (2) A shallow unconfined aquifer that contributes flow to the subbasin reach; and (3) A deep confined aquifer that is assumed to contribute to streamflow at some location outside the simulated basin (Neitsch *et al.*, 2009). The STATSGO soil data describes the Nahunta watershed soil profile as extending to a maximum of 2,515 mm below the surface. The calibrated SOL-K parameter (0.31; Table 1) dictates a relative increase in saturated hydraulic conductivity values throughout the Baseline model’s HRU soil profiles. The calibrated RCHR-DP parameter (0.03; Table 1) dictates that 97% of water moving below the soil profile and acting as groundwater recharge within a HRU enters the shallow aquifer to potentially impact streamflow while 3.0% enters the deep aquifer and is effectively lost from the system. The calibrated GWQMN parameter (445.7 mm; Table 1) dictates a relatively low threshold depth for groundwater to leave the shallow aquifer and enter the subbasin reach (the GWQMN maximum is 5,000 mm). In concert, these parameters portray a system within which water

moves quickly both vertically and laterally while water that moves below the soil profile is confined and quickly reaches the stream-network.

2.7. Scenario Definition

We executed a series of scenarios on our Baseline model at a daily time step for four calendar years (2001 to 2004) to evaluate the relative change in streamflow at the watershed outlet in response to potential resource management decisions affecting the abundance of GIWs in the Nahunta watershed. We defined the revised and calibrated Nahunta SWAT model (Sections 2.5 and 2.6), which includes modified GIW representations, as the “Baseline” model for future scenarios analyses (Table 2; Figure 6A). Scenario 1 represented the effect of filling or draining all GIWs within the watershed. Scenarios 2 and 3 represented filling or draining successively larger GIWs, as defined by calculated storage capacities (Figure 6B-C). Scenario 4 represented the effects of filling or draining only the larger GIWs with high storage volumes (Figure 6D). The criteria utilized to delineate Scenarios 2 through 4 were set by identifying natural breaks in the distribution of calculated GIW storage volumes (see Figure 2). Finally, Scenarios 5 and 6 represented the effects of filling or draining GIWs embedded within agricultural landscapes, accepting that a majority of historical wetland losses are attributed to agricultural activities (Hefner and Brown, 1984). Scenario 5 depicted the effects of filling or draining the entirety of a GIW with some portion of its area embedded within a row-crop agricultural landscape, e.g., an edge-of-field GIW; Figure 6E) while Scenario 6 depicted the effects of filling or draining only the portion of a GIW that exists within a row-crop area (Figure 6F). GIW areas removed from the Baseline model, as specified within each scenario, were reclassified as HRU areas with the original land cover, soils, and slope characteristics of each respective location (specified by the NLCD, STATSGO, and NED DEM) prior to the

incorporation of pothole HRUs in the SWAT model. Additional information regarding the manipulation of HRUs per each scenario is provided within the Supplementary Material.

2.8. Model Output and Flow Classification

We identified three types of model output to be evaluated within our study. The modified SWAT model was executed for the Baseline and Scenario 1 through 6 simulations to attain: (1) Average daily water balances for each of our pothole HRUs summarized across the four-year simulation period; (2) Average daily streamflow at the Nahunta watershed outlet summarized annually and seasonally; and (3) Average daily subbasin water balance data (e.g. surface flows, soil water content, etc.) summarized seasonally. We defined seasons as Spring (SP): March, April and May; Summer (SU): June, July, and August; Autumn (AU): September, October, and November; Winter (WI): December, January, and February.

We additionally classified baseflow and quickflow components of average daily streamflow simulations using a daily baseflow separation program (Lim, 2014). We defined quickflow as the quantity of flow occurring immediately after the onset of a precipitation event while baseflow is defined as the quantity of flow occurring for some time after the conclusion of the precipitation event (Hornberger *et al.*, 1998). Baseflow separation was calculated by inputting the SWAT-simulated daily average streamflow into *SWAT Bflow* (Lim, 2014), a baseflow separation program that utilizes the baseflow separation methodology described by Arnold and Allen (1999). Note that we did not equate cumulative daily subbasin groundwater flow from our SWAT model simulations (depicted as groundwater flow within the Nahunta watershed water balance) as baseflow at the Nahunta watershed outlet. A cumulative addition of subbasin groundwater flow cannot account for temporal lags that impact downstream flow contributions from headwater subbasins.

3. Results

3.1 GIW Water Balance

We first evaluated the average daily water balance for pothole HRUs (herein referred to as GIWs) within the Baseline model to assess the accuracy of our GIW representations. A substantial number of GIWs (18 of 41; ~44%) never had ponded water as evidenced by average daily water depths of 0.00 mm within the Baseline model simulations (Table 3). As part of these simulations, water was allowed to enter the GIW reservoirs via direct precipitation as well as surface flow (q_{day_j} Equation 5), and subsurface flows ($latq_j$ and gwq_j Equation 5) from HRUs draining to the GIW. Results suggested that direct precipitation was the dominant means of water input for ~66% of GIWs (Table 3). Water exited the GIWs via ET, groundwater seepage and overland spillage. Simulation results suggested that the sum of vertical and lateral seepage is the dominant means of water exiting the GIWs, followed by ET and then spillage (Table 3). Overland spillage from the GIWs occurred infrequently - spillage losses did not occur in ~66% of the GIWs and was less than 0.13 mm in the remainder of GIWs.

3.2 GIW Effects on the Daily Hydrograph

We compared the Baseline and Scenario 1 (100% GIW removal) simulated hydrographs for rainfall events of varied intensities as an initial exploratory assessment of the effects of GIWs on watershed hydrology. Event-based simulated hydrographs suggested that GIWs mitigate streamflow response to rainfall events and that this effect is more pronounced for higher rainfall events (Figure 7A). The event-based simulated hydrographs further suggested that the presence of GIWs in the landscape resulted in consistently higher simulated baseflow compared to that in their absence (Figure 7B). We supplemented our visual analysis via a comparison of the Baseline and Scenario 1 simulated streamflow exceedance probability distributions (Figure 8). The

exceedance curves further indicated that removal of GIWs from the landscape (Scenario 1) resulted in a considerably decreased probability of maintaining low flow conditions and a marginally greater probability of exceeding peak flow rates compared to the Baseline model (Figure 8).

3.3 GIW Effects on Annual Streamflow, Baseflow, and Quickflow

We evaluated variations in average annual streamflow, baseflow, and quickflow across all scenarios relative to the Baseline simulation. Simulation results indicated that removing GIWs from the watershed decreased baseflow, increased quickflow, and produced year-to-year variations in the sign and magnitude of average daily streamflow (Table 4). Scenario 1 (100% GIW removal) results suggested an approximately -9% to -39% year-to-year decrease in baseflow and approximately 11% to 14% year-to-year increase in quickflow. The Scenario 1 simulations, however, resulted in decreased average annual streamflow relative to the Baseline simulation during 2001, 2002, and 2004 (-9.1%, -5.6%, and -1.9%, respectively) but increased average annual streamflow relative to the Baseline simulation during 2003 (1.8%).

Scenarios 2 and 3 (removing GIWs with storage capacities less than 1000 m³ and 15,000 m³, respectively) also resulted in year-to-year decreases in average daily baseflow and increases in average daily quickflow relative to the Baseline. The magnitude of change relative to the Baseline simulation was greater for Scenario 3, however, for which a greater quantity of GIWs and cumulative storage capacity was removed. Note that Scenario 2 resulted in consistently positive changes to average daily streamflow relative to the Baseline (0.03% to 1.1%) while Scenario 3 resulted in a negative change from 2001 to 2002 (-3.2% and -1.2%, respectively) and positive change from 2003 to 2004 (3.7% and 1.1%, respectively). Scenario 4 (removing GIWs with storage capacities greater than 15,000 m³) resulted in consistent year-to-year decreases in

average daily streamflow (-0.71 to -5.28%) and baseflow (-5.9% to -16.5%) relative to the Baseline simulation. Conversely, Scenario 4 has consistent year-to-year increases in quickflow (4.7% to 5.8%) relative to the Baseline simulation.

Scenarios 5 and 6 had notably contrasting results as dictated by dissimilar scenario conditions. Scenario 5 (removing the whole of GIWs with some portion located in land designated row-agriculture) resulted in average daily streamflow, baseflow, and quickflow values approximate to those of Scenario 1 (removing all GIWs). Relative to the Baseline simulation, year-to-year average daily streamflow values for Scenario 5 were lower for 2001, 2002, and 2004 (-8.4%, -5.2%, and -1.7%, respectively) yet higher for 2003 (1.8%). Year-to-year average daily baseflow values were consistently less than those of the Baseline simulation (-8.7% to -35.64%) while year-to-year average daily quickflow values were consistently higher relative to the Baseline simulation (11.0% to 13.7%). Finally, relative to the Baseline simulation, Scenario 6 (removing only portions of GIWs located in areas designated as row-agriculture) had marginally lower year-to-year average daily streamflow values (-1.4% to -2.6%) and baseflow values (-2.8% to -5.4%).

3.4 GIW Effects on Seasonal Streamflow, Baseflow, and Quickflow

We also evaluated average seasonal changes in streamflow, baseflow, and quickflow across all scenarios relative to the Baseline simulation and found that GIWs have seasonally-dependent effects on average daily streamflow and baseflow, while quickflow effects are comparatively consistent across seasons (Table 5). Relative to the Baseline simulation, for example, Scenario 1 (removing all GIWs) resulted in decreased average daily streamflow during summer and autumn months (-16% and -6%, respectively) but increased average daily streamflow during spring and winter months (4% and 1%, respectively). Scenario 1 markedly

lowered average daily baseflow values (-45.2% and -32.2% relative to the Baseline) within summer and autumn months, yet average daily baseflow values changed only moderately within spring and winter months (-5% and -8% relative to the Baseline). Average daily quickflow values within Scenario 1 increased across seasons at 12% to 13% relative to the Baseline.

Scenarios 2 and 3 also have seasonally-dependent GIW effects though the magnitude of change was greater for Scenario 3 as dictated by that scenario's simulation of comparatively significant GIW removal. Relative to the Baseline simulation, Scenario 2 resulted in marginally decreased average daily streamflow values during summer months (-0.6%) and only marginally increased values during spring, autumn, and winter months (0.4% to 1.3%). Further, while Scenario 2 results suggested cross-seasonal increased average daily quickflow relative to the Baseline (2.4% to 2.5%), average daily baseflow values increased during spring months (0.2%) but decreased during summer, autumn, and winter months (-0.2% to -2.5%) relative to the Baseline simulation. Scenario 3 resulted in increased average daily streamflow values during spring and winter months (4.9% and 2.7%, respectively) relative to the Baseline simulation yet resulted in decreased average daily streamflow values during summer and autumn months (-7% and -0.7%, respectively). Further, Scenario 3 results suggested markedly decreased average daily baseflow values during summer and autumn months (-23.5% and -15.8%, respectively) yet comparatively smaller decreases in spring and winter months (-4.9% and -7.8%, respectively). Again, daily average quickflow resulting from the Scenario 3 simulation increased across seasons, though it increased at 11% to 12% relative to the Baseline.

Similar to the Scenario 3 results, Scenario 4 results suggested decreased average daily streamflow during summer, autumn and winter months (-1.2% to -8.2%) and increased average daily streamflow values during spring months (0.5%). Average daily baseflow resulting from

Scenario 4 demonstrated markedly decreased average daily baseflow during summer and autumn months (-19.4% and -14.1%, respectively) yet only moderate changes to baseflow during spring and winter months (-4.0% and -5.6%, respectively). Average daily quickflow values for Scenario 4 increased across seasons (4.8% to 5.5%).

Lastly, Scenarios 5 and 6 again had contrasting results. Scenario 5 simulation results suggested a moderately large decrease in average daily streamflow during summer months (-14.7%), a smaller decrease in winter months (-5.3%), and marginal increases in spring and winter months (3.9% and 0.9%, respectively). Average daily baseflow for Scenario 5 showed substantial decreases in summer and autumn months (-42.0% and -29.6%, respectively) yet displayed only moderate decreases in spring and winter months (-4.8% and -7.8%, respectively). Average daily quickflow values for Scenario 5 increased across seasons (11.6% to 12.7%). Scenario 6, in contrast, has cross-seasonal decreased average daily streamflow values (-1.1% to -3.5%), cross-seasonal decreased average daily baseflow values (-2.3% to -6.3%), and cross-seasonal increased average daily quickflow values (0.3% to 0.5%).

3.5 GIW Effects on the Watershed Water Balance

Finally, we compared components of the seasonal watershed water balance simulated by Scenario 1 (100% GIW removal, i.e., the “extreme” GIW removal scenario) to those simulated using the Baseline model to assess the range of GIW effects on watershed-scale hydrologic processes (Table 6). Results indicated that simulated potential evapotranspiration (PET) values did not change relative to the Baseline simulation. Simulated actual evapotranspiration (ET) was slightly higher within Scenario 1, an approximately 1.12% to 1.60% increase compared to the Baseline simulation across all seasons. Simulated soil water content decreased relative to the Baseline by approximately -2.28% to -2.30% across all seasons. Overland flows increased

relative to the Baseline by approximately 11.92% to 16.81% across all seasons. Groundwater flow decreased relative to the Baseline by approximately -6.54% to -7.33%. Total water yield from the modeled subbasins to the reach network increased in Scenario 1 compared to the Baseline simulation during summer and autumn months by approximately 2.56% and 0.52%, respectively, yet declined by -6.04% and -4.31% during spring and winter months, respectively.

4. Discussion

4.1 GIW Representation Accuracy

We modified a semi-distributed and semi-physically based watershed-scale hydrologic model to evaluate the aggregate watershed-scale effects of GIWs on downstream hydrology. Our study is one of the few that have targeted this objective (others include Vining, 2002; Wang *et al.*, 2008; Viger *et al.*, 2010; Almendinger *et al.*, 2011; McLaughlin *et al.*, 2014; Pomeroy *et al.*, 2014; Golden *et al.*, 2015), particularly in the Coastal Plain region of the US. Our study focused on the Nahunta watershed located in the Coastal Plain of North Carolina, USA, an area known to have a high density of potential GIWs (Lane *et al.*, 2012). Results suggest that our modified representation of GIWs in the SWAT model was consistent with field-based characterizations of regional GIWs in most respects. For example, as depicted within our model, GIWs were only sporadically ponded and ~44% have average daily storage depths of 0.0 mm (Table 3). Due to such infrequent ponding, the GIWs seldom approached storage capacity and rarely, if ever, resulted in overland spillage. The primary means by which water entered the GIWs within our simulations was via direct precipitation (average daily precipitation across all pothole HRUs was 3.09 mm; average daily inflows via surface and subsurface routing across all pothole HRUs was 2.65 mm). GIW outflow was primarily a function of groundwater seepage. Our GIW representation therefore generally conformed to field-based characterizations of these systems as

ephemerally ponded wetlands, which may be completely dry during periods of low precipitation and for which spillage events occur only during periods of excessive rainfall (Sharitz, 2003). Further, our representation was consistent with field-based studies that suggest inflow to regional GIWs is primarily a function of direct precipitation and outflow is a function ET and seepage to shallow groundwater (Lide, 1997; Sharitz, 2003; Pyzoha *et al.*, 2008).

We found that our representation of GIWs diverged relative to field-based characterizations of regional GIWs with respect to ET. Evapotranspiration losses averaged only 14% of total water losses across all pothole HRUs. Several studies have emphasized ET as an important component of regional wetland water balances (Lide, 1997; Sharitz, 2003). Lide (1997), for example, estimated ET to account for approximately 78% of all water losses from a regional wetland. To increase ET from the GIWs within the model, we experimented with the manipulation of the saturated hydraulic conductivity parameter that governs seepage from the GIWs to, in effect, increase the frequency of ponding and allow for greater quantities of daily ET. We specified a saturated hydraulic conductivity parameter of 0.013 mm hr^{-1} to describe seepage from a regional wetland (following Lide, 1997). This experiment resulted in nearly permanent ponding for all GIWs within the model – an unlikely occurrence in reality as regional wetlands have been characterized as having a range of conditions from permanent inundation to frequently dry (Sharitz, 2003). Thus, we elected to accept the simulated decrease in ET while allowing seepage processes to be dictated by a STATSGO (Schwarz and Alexander, 1995) data-derived saturated hydraulic conductivity parameter for the top soil horizon. This resulted in an average saturated hydraulic conductivity parameter of $561.41 \text{ mm hr}^{-1}$ for pothole HRUs, a value (1) representative of the generally porous soils within the study area and (2) the parameter's requirement in the model to effectively govern both vertical and lateral seepage from a GIW. Our

depiction of GIW outflow as primarily determined by seepage processes conforms to published descriptions of regional GIWs as “flow-through” systems (Pyzoha *et al.*, 2008) as well as more general descriptions of GIWs hydrology as driven by subsurface lateral flow in landscapes dominated by highly porous soils (Winter, 2003).

4.2 GIW Effects on Watershed Hydrology

A review by Acreman and Holden (2013) concluded that wetlands attenuate peak flows. This axiom was supported by our findings, as hydrograph comparisons between the Baseline and Scenario 1 demonstrated that GIWs decreased peak flows, particularly following high rainfall events (Figure 7A). We attributed peak flow mitigation effects to the intermediate storage functionality (or lag time effect, *sensu* Leibowitz and Brooks (2008)) of GIWs in the landscape. When a rainfall event occurred within our model, increased quantities of water entered the GIWs (i.e., the SWAT pothole storage reservoirs) via direct precipitation, overland flow, and subsurface flow from upgradient HRUs. This event water was transported to the reach network only after seeping through the GIW subsurface and then leaving the shallow aquifer as groundwater flow. Without the GIWs (i.e., Scenario 1), this quantity of water was immediately routed to the reach network. Simulated water balances suggested that GIWs in the watershed rarely reach storage capacity such that high rainfall events simply route more flow to the storage reservoirs but do not induce spillage and transport to the stream (Table 3). Thus, the Baseline and Scenario 1 hydrographs diverged following high rainfall events (Figure 7A). These findings are consistent with publications reporting that upland embedded wetlands, peatlands, and lakes functioned as intermediate water storage areas that govern connectivity dynamics to the watershed outlet (see Novitzki, 1985; Johnston *et al.*, 1990; Phillips *et al.*, 2011).

Our results also indicated that GIWs exerted seasonally-dependent simulated effects on baseflow. Relative to the Baseline simulation, Scenario 1 lowered baseflow approximately 45% and 32% during autumn and summer months, respectively, and approximately 5% in spring and 8% in winter months (Table 5). Therefore, both baseflow (Table 5), calculated using the baseflow separation program, and groundwater flows, simulated as a component of watershed's water balance (Table 6), decreased in response to 100% GIW removal. We attributed the decreased annual baseflow and groundwater flow from Scenario 1 simulations to the seepage (i.e., groundwater recharge and storage) effects associated with GIW removal from the landscape. We further attributed the marked impact of GIWs on the maintenance of baseflow conditions during autumn and summer months to lower overall baseflow rates during those seasons (Table 5). Our findings regarding the effects of GIWs upon baseflow are consistent with general understandings of wetlands as systems that contribute to baseflow via groundwater recharge, particularly in settings with porous, highly permeable soils such as the Nahunta (Winter, 2003; McLaughlin *et al.*, 2014).

Simulation results also suggested that GIWs impact multiple components of the watershed's water balance. Scenario 1 resulted in a small but notable increase in ET relative to the Baseline across all seasons. Wetlands evapotranspire more water than other land use types because of their frequent inundation and saturation conditions (Mitsch and Gosselink, 2000; Bullock and Acreman, 2003). Thus, we had anticipated that as GIWs were removed from the model and simulated as other land uses within Scenario 1, ET would decrease within the system. We explain our results by noting that the majority of land identified as GIWs within the NC-CREWS was classified as forest (approximately 65% in 2006 NLCD; Fry *et al.*, 2011). The conversion of GIWs to forested land resulted in increased watershed ET for two primary reasons.

First, pothole HRUs were devoid of vegetation as represented in our model. The forest HRUs that replaced the removed GIWs have high canopy precipitation interception values in the model (fitted through the maximum canopy storage parameter in the calibration procedure) and consequently higher ET rates than those simulated for vegetation-free pothole HRUs. Second, most GIWs were only sporadically ponded (Table 3). While GIWs have higher quantities of ET while ponded, they were rarely ponded and therefore have a decreased capacity for ET compared to the forest HRUs. Thus, their removal on the landscape increased watershed-scale ET.

The watershed's simulated water balance indicated that GIWs decreased overland flow yet increased soil water content and groundwater flow. Relative to the Baseline simulation, surface flow increased approximately 12% to 17% with Scenario 1 across all seasons. We attribute the simulated increase in surface flow within Scenario 1 to omission of the intermediate storage effects of the GIWs in the landscape. While Scenario 1 simulated surface flow per the model's runoff-infiltration estimation routine, the Baseline simulation allows overland flow from GIWs only during spillage events – events shown to rarely occur (Table 3). We attributed decreased soil water content and groundwater flow within Scenario 1 to removal of the GIWs and the associated decreased capacity for groundwater recharge throughout the watershed.

4.3 Scenario Implications

Scenario 1 (100% GIW removal) represented the extreme of the simulated conditions and thus the aggregate effect of all GIWs within the study area on watershed hydrology. Subsequent scenarios provided additional insights regarding the hydrologic significance of particular GIW sub-sets as well as the consequences of alternative resource management strategies. Scenario 2 results, for example, suggested that smaller yet more abundant GIWs (storage capacities less than 1,000 m³) (Figure 2) can have limited but measurable effects upon downgradient baseflow,

particularly within summer months (i.e. Scenario 2 resulted in a -2.5% decrease in baseflow during summer months relative to the Baseline simulation). This observation aligns with conclusions drawn by McLaughlin *et al.* (2014) regarding the effect of smaller wetlands in decreasing water table and baseflow variability. Scenario 2 results, however, also suggested that smaller GIWs affect quickflow (seasonal increases of approximately 2.5%).

Furthermore, comparisons between Scenarios 3 and 4 permitted an examination of the impact of numerous yet smaller GIWs versus fewer yet larger GIWs within the study area. Results suggest that smaller GIWs have a substantially greater influence on quickflow relative to the larger GIWs. For instance, Scenario 3 simulations resulted in increased average daily quickflow 10.8% to 11.9% across seasons relative to the Baseline simulation, while Scenario 4 (in which only large GIWs remained) results suggested moderately increased daily quickflow (4.8% to 5.5%) across all seasons relative to the Baseline simulation. Thus, Scenario 3 (removing GIWs with storage capacities less than 15,000 m³) affected average daily quickflow at nearly twice the rate of Scenario 4. The Scenario 3 and Scenario 4 simulation results additionally indicated that relative to larger GIWs, smaller GIWs have a greater capacity to increase baseflow during summer and autumn months (Scenario 3 results suggested summer and autumn baseflow decreases of -23.5% and -15.8% while Scenario 4 results reflected somewhat lower changes in baseflow (-19.4% and -14.1%, respectively)). As with the Scenario 2 results, this finding is indicative of the relative importance of smaller versus larger GIWs in regulating baseflow, as observed by McLaughlin *et al.* (2014). Conversely, Scenarios 3 and 4 results suggest that larger GIWs have a greater capacity to increase baseflow during spring and winter months relative to smaller GIWs (Scenario 4 has decreases of -4.0% and -5.6% while Scenario 3 has decreases of -1.6% and -3.6%, respectively).

Finally, comparisons between Scenarios 5 and 6 afford inferences regarding the hydrologic significance of GIW losses attributable to agriculture. Substantial historical wetland losses have been observed in the southeastern U.S., particularly within eastern North Carolina (Hefner and Brown, 1984). Cashin *et al.* (1992), for example, found that 51.3% of pre-settlement wetlands have been lost within the North Carolina Coastal Plain and that 42.2% of losses are attributable to agricultural activities. Scenario 5 evaluates the extreme of plausible agricultural-attributable GIW drainage outcomes (removing the whole of GIWs with some portion located in land designated row-agriculture) and indicates significant downgradient hydrologic effects. In fact, Scenario 5 results were approximate to Scenario 1 results (100% GIW removal). Alternatively, Scenario 6 simulation results suggested that removing only portions of GIWs located in land designated as row-agriculture resulted in decreased baseflow across seasons, particularly in the summer months (-6.3% relative to the Baseline simulation).

5. Method Assumptions and Limitations

We present a novel contribution toward quantifying the potential hydrologic effect of GIWs at a watershed scale with additional spatial detail compared to previous methods. However, all modeling methods necessarily have certain limitations. For example, our method did not represent “spill-and-fill” inter-GIW hydrologic relationships. Spill-and-fill occurs where an up-slope GIW fills to capacity and excess spillage drains to a down-slope GIW. This process has been observed between prairie potholes and California vernal pools (Leibowitz and Nadeau, 2003; Zedler, 2003; Rains *et al.*, 2006; Leibowitz and Brooks, 2008) but is not likely to occur amongst wetlands of the Southeastern Coastal Plain. Our method routed excess spillage directly to the subbasin reach without interception from intermediate GIW storage reservoirs. Further, similar inter-wetland subsurface flows may occur in addition to temporal lags resulting from

these fill-spill processes but were not represented within our method. While our method therefore potentially overestimated the quantity and rate of overland and subsurface flows entering the reach network (thereby underestimating the hydrologic impact of GIWs), watershed GIWs did not frequently exhibit overland flow between GIWs and between GIWs and the reach network (Sharitz, 2003). Therefore, our approach did not present substantial limitations in this regard for the study area.

Further, while our method expanded previous work by making advancements toward spatially-explicit GIW representations in watershed simulation analyses, we were bound by the model structure to depict all GIWs within a subbasin via a lumped pothole HRU representation. Two or more GIWs within a single subbasin were necessarily represented as a singular and larger pothole HRU with a cumulative storage capacity. HRUs within the combined drainage area of both GIWs were then made to drain to the larger pothole representation. This limited our capacity to evaluate the effects of specific GIWs where multiple GIWs existed within a singular subbasin. This model limitation may be minimized in the future by the development of a SWAT model with smaller subbasin sizes such that each subbasin contains only one GIW representation. However, decreasing subbasin sizes may induce prohibitively large computation time requirements depending on application specifics. Regardless, our method did represent the aggregate effects of subbasin GIWs on the watershed's downstream hydrograph, which was the evaluative goal of this study.

Lateral subsurface seepage from GIWs may be an important component of their water balances in this region (Pyzoha *et al.*, 2008). Our model represented both vertical and lateral subsurface seepage from a GIW as water that enters the pothole HRU's shallow aquifer before reaching the stream network. However, because SWAT affords parameterization of only one

hydraulic conductivity value to simulate seepage from the GIWs, seepage rates for the GIW reservoir in the model necessarily represented vertical and lateral aggregate values. Thus, the hydraulic conductivity parameter that governs aggregate GIW seepage rates within our model (561.41 mm hr⁻¹) was high yet consistent with (1) an aggregate vertical-lateral value and (2) the high porosity loamy sand and sandy loam soils of the study area (Schwarz and Alexander, 1995). This value is also approximate to the rate of 433.3 mm hr⁻¹ used by Wang *et al.* (2008) to simulate wetland hydrologic effects using SWAT. However, because of this aggregate approach, saturated hydraulic conductivity values and simulated seepage from pothole HRU's should not be directly compared to field-based characterizations of distinct vertical or lateral seepage processes. Additionally, as we tailored our GIW representation to depict seepage within a landscape dominated by highly porous soils, conclusions drawn regarding GIW aggregate effects are not immediately transferable to GIWs in disparate landscapes – such as within the North American Prairie Pothole Region.

Our model revisions improve upon current GIW hydrologic connectivity processes in SWAT, particularly for our study watershed. These revisions do not, however, result in increased model performance as measured by standard performance criteria metrics. To evaluate the impact of our revisions on model performance, we constructed an alternative SWAT model employing the conventional wetland representation to depict study area GIWs. We specified descriptive parameters for the conventional wetlands (e.g., the parameters describing the fraction of each subbasin draining to the conventional wetland and the storage capacity of the conventional wetland reservoir) using the NC-CREWS data utilized by our revised approach. We then applied the parameter set utilized for the Baseline model for the conventional wetland model. This conventional wetland SWAT model had NSE, RSR and PBIAS values of 0.67, 0.58,

and 10.2, respectively. Recall that the calibrated Baseline model had NSE, RSR and PBIAS values of 0.66, 0.58, and -10.8, respectively. Therefore, our revised approach resulted in relatively similar performances, as measured by the NSE and RSR. While the conventional wetland approach had a tendency to overestimate streamflow (PBIAS value of 10.2), our revised approach had a tendency to underestimate streamflow (PBIAS value of -10.8). However, we emphasize that differences in model performance as measured by standard performance criteria metrics should not be applied to evaluate the absolute utility of model revisions. Performance criteria metrics such as the NSE are intended to evaluate a model's capacity to predict streamflow values – not the model's capacity to accurately represent hydrologic processes within a system, which was a key goal of our approach. Future work could address the issue of performance criteria across modes of GIW representation (i.e. the conventional wetland, the unmodified pothole, the HEW, and our modified pothole). However, a more comprehensive evaluation was beyond the scope of the current study.

We did not include an explicit representation of riparian wetlands within our model. We aimed to account for these systems via SWAT's representation of floodplain dynamics and by calibrating parameters governing the rate of water transport through the simulated stream network (e.g., CH-K2 and CH-N2 characterize the saturated hydraulic conductivity for the main channel alluvium and the Manning's "N" value for the main channel, respectively). Future work should consider testing approaches that explicitly represent riparian wetlands, such as the development and application of SWAT extension modules similar to Liu *et al.* (2008).

Finally, future work must evaluate the model over longer simulation periods, against field data, and alternative modes of wetland simulation. We restricted our analysis to our calibration period (including both "wet" and "dry" years with annual precipitation below and above one

standard deviation of the mean annual precipitation for the period 1990 through 2010). However, a longer simulation period and a validation period would strengthen our analysis of GIW aggregate hydrologic effects and allow projections of future conditions. Additionally, field data (e.g., soil moisture measurements, wetland and local groundwater stage levels) should be utilized to validate our model as made available. Further, future research should evaluate simulated wetland water balance data given via our modified pothole HRU approach against water balance data given via alternative representations (e.g. the conventional wetland representation and the HEW representation). Such an evaluation will advance our understanding of how alternative representations of GIWs in watershed hydrologic modeling may affect our current understanding of their watershed-scale effects.

6. Summary and Conclusions

"Geographically isolated" wetlands (GIWs) support an array of ecological processes (Creed *et al.*, 2003; Leibowitz and Nadeau, 2003; Pomeroy *et al.*, 2014) yet have experienced historical losses worldwide (McCauley and Jenkins, 2005; Johnston, 2013; McCauley *et al.*, 2013) - as have all wetlands (Dahl, 2011). Regulatory protections for GIWs within the US have been challenged via legal proceedings that have resulted in protection of these systems under the US Clean Water Act, in-part, only where there is a significant effect of a GIW or GIWs on traditional navigable waters (see "Rapanos," 547 US 715 2006). To most effectively manage watersheds and their associated surface water components (e.g., wetlands, uplands, and stream systems) there is a clear need for methods capable of evaluating the potential aggregate hydrologic effect of GIWs on the downstream hydrograph.

In this study, we quantified the watershed-scale aggregate effects of GIWs on downstream hydrology by developing a novel simulation method that improves the

representation of GIWs and their hydrologic connectivity processes in a watershed hydrologic model. We specifically modified the Soil and Water Assessment Tool (SWAT) by both implementing an alternative hydrologic response unit (HRU) definition to more accurately represent GIWs and GIW connectivity relationships and by modifying the model's source code to allow subsurface inflow into our GIW representations, an important process in the studied watershed. We applied our modified model to a 202 km² watershed in the North Carolina Coastal Plain, an area with a large population of GIWs. This allowed us to construct a "Baseline" model within which all GIWs within the study area were represented. To better understand the impacts of potential management decisions affecting the extent of GIWs in the basin, we developed a series of scenarios designed to evaluate the aggregate hydrologic effects of all GIWs as well as specific GIW sub-sets by removing GIWs from the Baseline model.

Our primary conclusion is that GIWs, in-aggregate, have a substantial effect on watershed-scale water balances in the studied watershed by increasing seasonally-defined subsurface storage and groundwater flow. This conclusion suggests that GIWs are important hydrologic components within the studied watershed, and that incorporation of GIWs into best management practices at the landscape-level would improve management of runoff and subsequent effects, such as flooding. We also determined that GIWs attenuate downstream peak flows and have a greater influence following high rainfall events within the studied watershed, an important conclusion for stormwater management and of particular interest in regions that are affected by hurricanes or may experience higher rates of precipitation as a result of climate change. Finally, we found that GIWs have seasonally-dependent effects on downstream baseflow in the studied watershed, an important finding for maintaining streamflows that sustain the integrity of the aquatic ecosystems (Poff and Zimmerman, 2010) as well as mitigating low flow

828 events that affect alternative stream waters uses (e.g., agricultural or drinking water
829 withdrawals).

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Parameter	P-Value ^b	Min	Max	Calibrated Value	Description (units, if applicable)
ALPHA-BF	0.28	0.00	1.00		Baseflow alpha factor
CANMX ^a	< 0.00	0.00	100	71.41	Maximum canopy storage (mm)
CH-K2 ^c	0.34	0.00	500	0.23 ^d	Effective hydraulic conductivity in main channel alluvium (mm hr ⁻¹)
CH-N2 ^c	0.21	0.01	0.30	0.16 ^d	Manning's "N" value for the main channel
CN2 ^a	< 0.00	35.00	98	0.02 ^d	SCS runoff curve number
EPCO	0.74	0.00	1.00		Plant uptake compensation factor
ESCO	0.59	0.00	1.00		Soil evaporation compensation factor
GW-DELAY	0.29	0.00	500		Groundwater delay (days)
GW-REVAP	0.85	0.02	0.20		Groundwater "revap" coefficient
GWQMN ^a	< 0.00	0.00	5000	445.7	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
RCHR-DP ^a	< 0.00	0.00	1.00	0.03	Deep aquifer percolation fraction
REVAPMN	0.73	0.00	500		Threshold depth of water in the shallow aquifer for "revap" to occur (mm)
HRU-SLP	0.23	0.00	1.00		Average slope steepness (m m ⁻¹)
SLSUBBSN	0.66	10.00	150		Average slope length (m)
SOL-ALB	0.59	0.00	0.25		Moist soil albedo
SOL-AWC	0.89	0.00	1.00		Available water capacity of the soil layer (mm mm ⁻¹)
SOL-K ^a	< 0.00	0.00	2000	0.31 ^d	Saturated hydraulic conductivity (mm hr ⁻¹)
SOL-Z	0.96	0.00	3500		Depth from soil surface to bottom of the soil layer (mm)
SURLAG ^a	< 0.00	0.00	10	0.29	Surface runoff lag time (hours)

^a Sensitive parameter
^b P-value as determined by initial calibration run; threshold for sensitivity determination was 0.05
^c Parameter included in calibration despite not meeting P-value threshold; see text for explanation
^d Parameter manipulated with a relative change (i.e. parameter value is multiplied by the sum of the calibrated value and 1)

Table 1. Parameters calibrated using the Baseline model.

Model/ Scenario	Description	Simulated GIWs	% GIWs Removed	% Storage Removed	Simulated GIW Storage (10 ⁴ m ³)				Simulated GIW Area (km ²)			
					Min.	Max.	Avg.	Sum	Min.	Max.	Avg.	Sum
Baseline	All GIWs simulated	280	0	0	< 0.1	173.2	7.7	2168.7	< 0.1	1.2	< 0.1	10.2
1	All GIWs removed	0	100	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	GIWs with volume < 1000 m ³ removed	173	38	2	1.1	173.2	12.2	2117.6	< 0.1	1.2	0.1	9.6
3	GIWs with volume < 15000 m ³ removed	25	91	33	15.7	173.2	57.9	1448.1	< 0.1	1.2	0.2	5.3
4	GIWs with volume > 15000 m ³ removed	197	30	68	0.5	14.9	3.6	704.1	< 0.1	0.2	< 0.1	4.6
5	GIWs on agricultural land removed (full)	44	84	94	< 0.1	40.4	2.7	120.9	< 0.1	0.1	< 0.1	0.5
6	GIWs on agricultural land removed (partial)	269 ^a	4	20	< 0.1	154.1	6.4	1726.7	< 0.1	1.0	< 0.1	8.6

^a Includes partially drained GIWs

1021

1022 **Table 2.** Scenario definitions.

1023

Subbasin	Area (km ²)	Daily Average (Standard Deviation) (mm)					
		Inflow ^a	Precip. ^b	ET	Seepage ^c	Spill.	Depth ^d
1	0.08	4.13 (9.00)	3.09 (8.12)	1.00 (0.37)	6.17 (14.72)	0.04 (1.11)	0.00 (0.00)
2	0.20	6.28 (13.99)	3.09 (8.12)	1.05 (0.45)	8.32 (16.62)	0.00 (0.00)	2.42 (16.19)
3	0.44	1.58 (3.36)	3.09 (8.12)	0.73 (0.37)	3.94 (5.69)	0.00 (0.00)	0.92 (11.29)
4	0.33	1.92 (3.90)	3.09 (8.12)	0.85 (0.33)	4.16 (7.39)	0.00 (0.00)	0.51 (7.27)
5	0.04	1.50 (3.52)	3.09 (8.12)	0.67 (0.34)	3.92 (10.46)	0.00 (0.00)	0.00 (0.00)
6	0.04	4.53 (9.30)	3.09 (8.12)	1.11 (0.51)	6.38 (14.12)	0.13 (2.59)	0.00 (0.00)
7	1.07	2.58 (5.44)	3.09 (8.12)	0.98 (0.76)	4.70 (3.23)	0.00 (0.00)	13.70 (46.17)
8	0.20	2.17 (5.01)	3.09 (8.12)	0.77 (0.24)	4.49 (11.17)	0.00 (0.00)	0.15 (2.43)
9	0.26	3.35 (7.47)	3.09 (8.12)	0.85 (0.35)	5.59 (10.90)	0.00 (0.00)	0.96 (8.76)
10	0.08	6.23 (14.60)	3.09 (8.12)	1.08 (0.48)	8.24 (20.10)	0.00 (0.00)	0.09 (2.19)
11	0.07	8.27 (19.81)	3.09 (8.12)	1.17 (0.55)	10.14 (24.70)	0.05 (1.79)	0.11 (2.47)
12	0.18	1.27 (2.51)	3.09 (8.12)	0.70 (0.19)	3.65 (9.36)	0.01 (0.27)	0.02 (0.44)
13	0.01	1.08 (3.20)	3.09 (8.12)	0.54 (0.45)	3.64 (10.36)	0.00 (0.00)	0.00 (0.00)
14	0.30	1.28 (2.56)	3.09 (8.12)	0.73 (0.26)	3.62 (6.99)	0.02 (0.71)	0.17 (4.30)
15	0.25	3.43 (7.06)	3.09 (8.12)	1.00 (0.36)	5.52 (10.91)	0.00 (0.00)	0.73 (7.35)
16	0.03	5.79 (13.47)	3.09 (8.12)	1.12 (0.59)	7.73 (18.86)	0.04 (1.41)	0.00 (0.00)
17	0.21	2.67 (5.85)	3.09 (8.12)	0.89 (0.27)	4.87 (11.28)	0.00 (0.00)	0.28 (3.70)
18	0.06	4.85 (12.37)	3.09 (8.12)	0.93 (0.39)	6.92 (17.84)	0.09 (2.26)	0.00 (0.00)
19	0.30	1.03 (2.38)	3.09 (8.12)	0.61 (0.24)	3.51 (7.11)	0.00 (0.00)	0.20 (4.59)
20	0.01	3.15 (7.55)	3.09 (8.12)	0.84 (0.58)	5.40 (13.86)	0.00 (0.00)	0.00 (0.00)
21	0.05	8.02 (19.73)	3.09 (8.12)	1.13 (0.60)	9.98 (25.35)	0.00 (0.00)	0.02 (0.79)
22	0.18	2.25 (4.95)	3.09 (8.12)	0.81 (0.23)	4.53 (11.10)	0.00 (0.14)	0.11 (1.93)
24	0.05	0.47 (1.45)	3.09 (8.12)	0.36 (0.25)	3.20 (9.08)	0.00 (0.00)	0.00 (0.00)
25	0.24	0.57 (1.19)	3.09 (8.12)	0.52 (0.18)	3.14 (7.65)	0.00 (0.00)	0.04 (1.78)
26	0.11	2.66 (6.15)	3.09 (8.12)	0.80 (0.27)	4.94 (12.69)	0.00 (0.00)	0.02 (0.69)
27	0.01	0.32 (0.99)	3.09 (8.12)	0.37 (0.36)	3.04 (8.54)	0.00 (0.00)	0.00 (0.00)
30	0.42	1.39 (3.25)	3.09 (8.12)	0.69 (0.37)	3.79 (5.83)	0.00 (0.00)	0.80 (10.21)
31	0.69	1.16 (2.42)	3.09 (8.12)	0.69 (0.45)	3.56 (3.58)	0.00 (0.00)	1.93 (17.82)
33	0.03	3.54 (7.58)	3.09 (8.12)	0.98 (0.46)	5.59 (12.92)	0.07 (1.58)	0.00 (0.00)
34	0.15	1.30 (2.94)	3.09 (8.12)	0.68 (0.22)	3.71 (9.84)	0.00 (0.00)	0.01 (0.37)
35	0.04	6.39 (14.28)	3.09 (8.12)	1.06 (0.56)	8.42 (19.69)	0.00 (0.00)	0.00 (0.00)
36	0.12	0.25 (0.51)	3.09 (8.12)	0.38 (0.19)	2.95 (8.21)	0.00 (0.16)	0.00 (0.00)
37	0.22	0.54 (1.09)	3.09 (8.12)	0.52 (0.17)	3.12 (8.18)	0.00 (0.08)	0.02 (0.88)
38	0.01	0.52 (1.28)	3.09 (8.12)	0.47 (0.35)	3.14 (8.71)	0.00 (0.00)	0.00 (0.00)
40	0.04	4.34 (9.53)	3.09 (8.12)	0.99 (0.43)	6.45 (15.57)	0.00 (0.00)	0.00 (0.00)
41	0.05	2.27 (4.87)	3.09 (8.12)	0.93 (0.38)	4.35 (10.22)	0.08 (1.83)	0.00 (0.00)
43	0.00	1.77 (4.71)	3.09 (8.12)	0.63 (0.52)	4.23 (11.66)	0.00 (0.00)	0.00 (0.00)
44	0.15	0.41 (0.93)	3.09 (8.12)	0.43 (0.18)	3.08 (8.55)	0.00 (0.00)	0.00 (0.00)
45	0.10	2.33 (5.21)	3.09 (8.12)	0.80 (0.27)	4.57 (11.39)	0.06 (1.36)	0.00 (0.00)
46	0.02	0.92 (2.19)	3.09 (8.12)	0.56 (0.37)	3.45 (8.64)	0.00 (0.00)	0.21 (2.35)
47	0.39	0.18 (0.44)	3.09 (8.12)	0.37 (0.24)	2.90 (4.91)	0.00 (0.02)	0.18 (5.57)

^a Inflow is the sum of surface and subsurface loadings from HRUs draining to a GiW

^b The same weather gauge was used for all simulated subbasins

^c Seepage is the aggregate of vertical and lateral seepage from the pothole HRU

^d Depth at end of each time step

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1025 **Table 3.** Average daily values (and standard deviation) for each pothole HRU's water balance
1026 component across the full simulation period (2001 through 2004) under Baseline conditions.

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		Average Daily ($\text{m}^3 \text{s}^{-1}$)				Relative Change (%)			
		2001	2002	2003	2004	2001	2002	2003	2004
Baseline	Streamflow	1.33	1.51	3.42	2.24	NA	NA	NA	NA
	Baseflow	0.69	0.76	2.02	1.34	NA	NA	NA	NA
	Quickflow	0.64	0.75	1.40	0.91	NA	NA	NA	NA
Scenario 1	Streamflow	1.22	1.43	3.49	2.20	-9.12	-5.60	1.78	-1.87
	Baseflow	0.50	0.58	1.85	1.17	-38.53	-30.55	-9.30	-14.01
	Quickflow	0.72	0.84	1.64	1.03	11.26	11.60	14.25	11.97
Scenario 2	Streamflow	1.33	1.51	3.46	2.25	0.03	0.28	1.09	0.58
	Baseflow	0.68	0.75	2.02	1.33	-2.07	-1.84	-0.10	-0.64
	Quickflow	0.65	0.76	1.44	0.93	2.26	2.30	2.77	2.34
Scenario 3	Streamflow	1.29	1.49	3.56	2.27	-3.24	-1.23	3.72	1.10
	Baseflow	0.58	0.65	1.95	1.25	-20.06	-16.85	-3.64	-6.74
	Quickflow	0.71	0.84	1.61	1.02	10.40	10.90	12.69	10.81
Scenario 4	Streamflow	1.27	1.45	3.40	2.19	-5.28	-4.03	-0.71	-2.25
	Baseflow	0.60	0.66	1.91	1.24	-16.53	-14.72	-5.85	-7.53
	Quickflow	0.67	0.78	1.49	0.95	4.75	4.97	5.84	4.67
Scenario 5	Streamflow	1.23	1.43	3.49	2.20	-8.39	-5.15	1.77	-1.67
	Baseflow	0.51	0.59	1.86	1.18	-35.64	-28.52	-8.70	-13.09
	Quickflow	0.72	0.84	1.63	1.02	11.03	11.31	13.74	11.52
Scenario 6	Streamflow	1.30	1.47	3.38	2.20	-2.57	-2.36	-1.41	-1.80
	Baseflow	0.66	0.72	1.97	1.29	-5.36	-5.16	-2.82	-3.19
	Quickflow	0.64	0.75	1.41	0.91	0.30	0.29	0.55	0.16

Table 4. Average daily simulated streamflow, separation of streamflow into baseflow and quickflow components, and relative percent change for each component under Baseline and Scenario 1 through Scenario 6 for each year during the simulation period.

		Average Daily ($\text{m}^3 \text{s}^{-1}$)				Relative Change (%)			
		SP	SU	AU	WI	SP	SU	AU	WI
Baseline	Streamflow	2.91	1.47	2.02	2.11	NA	NA	NA	NA
	Baseflow	1.61	0.89	1.04	1.27	NA	NA	NA	NA
	Quickflow	1.30	0.58	0.97	0.84	NA	NA	NA	NA
Scenario 1	Streamflow	3.03	1.27	1.91	2.13	3.97	-15.73	-5.79	0.94
	Baseflow	1.53	0.61	0.79	1.17	-5.17	-45.22	-32.18	-8.25
	Quickflow	1.49	0.66	1.12	0.96	13.32	11.71	12.81	12.09
Scenario 2	Streamflow	2.95	1.46	2.03	2.13	1.27	-0.59	0.42	0.85
	Baseflow	1.62	0.87	1.03	1.26	0.18	-2.52	-1.61	-0.21
	Quickflow	1.33	0.59	1.00	0.86	2.53	2.35	2.52	2.44
Scenario 3	Streamflow	3.06	1.37	2.00	2.17	4.89	-6.99	-0.72	2.69
	Baseflow	1.59	0.72	0.90	1.22	-1.61	-23.49	-15.76	-3.60
	Quickflow	1.47	0.65	1.10	0.95	11.88	11.31	11.59	10.84
Scenario 4	Streamflow	2.92	1.36	1.94	2.08	0.49	-8.23	-3.95	-1.18
	Baseflow	1.55	0.74	0.91	1.20	-3.95	-19.38	-14.05	-5.58
	Quickflow	1.37	0.61	1.03	0.88	5.49	5.37	5.04	4.76
Scenario 5	Streamflow	3.03	1.28	1.92	2.13	3.88	-14.66	-5.26	0.92
	Baseflow	1.54	0.63	0.80	1.17	-4.84	-42.03	-29.61	-7.76
	Quickflow	1.49	0.66	1.11	0.95	12.86	11.56	12.37	11.63
Scenario 6	Streamflow	2.88	1.42	1.97	2.08	-1.06	-3.53	-2.27	-1.45
	Baseflow	1.58	0.84	0.99	1.23	-2.26	-6.27	-4.88	-2.63
	Quickflow	1.30	0.58	0.98	0.85	0.34	0.53	0.36	0.27

Table 5. Average daily simulated streamflow, separation of streamflow into baseflow and quickflow components, and relative percent change for each component under Baseline and Scenario 1 through Scenario 6. SP = Spring; SU = Summer; AU = Autumn; WI = Winter.

		Average Daily (mm)				Relative Change (%)			
		SP	SU	AU	WI	SP	SU	AU	WI
Baseline	Precipitation	2.96	4.25	1.82	1.21	NA	NA	NA	NA
	PET	2.12	1.80	2.50	1.98	NA	NA	NA	NA
	ET	0.80	0.85	1.11	0.74	NA	NA	NA	NA
	Soil Water Content	440.11	447.32	447.60	443.13	NA	NA	NA	NA
	Surface Flow	0.03	0.59	0.36	0.09	NA	NA	NA	NA
	Groundwater Flow	0.93	0.92	0.92	0.93	NA	NA	NA	NA
	Total Water Yield	0.98	1.79	1.34	1.06	NA	NA	NA	NA
Scenario 1	Precipitation	2.96	4.25	1.82	1.21	0.00	0.00	0.00	0.00
	PET	2.12	1.79	2.49	1.98	-0.15	-0.11	-0.08	-0.06
	ET	0.81	0.86	1.13	0.74	1.26	1.55	1.60	1.12
	Soil Water Content	430.23	437.33	437.61	433.17	-2.30	-2.29	-2.28	-2.30
	Surface Flow	0.03	0.67	0.42	0.11	16.81	11.92	13.50	15.04
	Groundwater Flow	0.87	0.86	0.86	0.86	-7.17	-6.75	-6.54	-7.33
	Total Water Yield	0.92	1.83	1.35	1.01	-6.04	2.56	0.52	-4.31

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1039 **Table 6:** Average daily simulated subbasin water balances. Simulated values for the Baseline
1040 and Scenario 1 (100% GIW removal) models are presented. Relative percent change from the
1041 Baseline values are presented for Scenario 1. Spring; SU = Summer; AU = Autumn; WI =
1042 Winter.

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FIGURE LEGEND:

Figure 1. (A) The Nahunta watershed with the 2006 NLCD, high-resolution NHD stream network, and USGS gage #02091000. (B) The Nahunta watershed with the SWAT delineated reach network and NC-CREWS GIWs.

Figure 2. Histogram of GIW volumetric storage capacities within the study watershed. Storage capacities were calculated using a methodology demonstrated by Lane and D'Amico (2010).

Figure 3. Revisions to HRU boundaries provide an improved representation of GIW hydrologic and spatial relations. These revisions are illustrated within a simplified subbasin. The first figure (A) shows the standard SWAT (i.e., unmodified) subbasin and HRUs (without consideration of GIWs). The second figure (B) shows a GIW and the GIW's upgradient drainage area delineated within the subbasin. The third figure (C) shows the results of our redefinition HRUs boundaries, which conform to the boundaries of the GIW and its upgradient drainage area. Using the new HRU definition, outflow from HRUs 3 and 4 are routed to HRU 5 and HRU 5 is defined as a pothole HRU (i.e., a GIW).

Figure 4. Conceptual model of HRU and pothole HRU interaction with our model modifications: q_{day} = overland surface flow; $latq$ = lateral subsurface flow within the soil profile; gwq = groundwater flow from the shallow aquifer.

Figure 5. USGS streamflow observations from gauge #02091000 at Nahunta Swamp near Shine, NC; NCDC precipitation observations from Goldsboro Seymour Johnson AFB, NC; and Baseline model simulated streamflow at Nahunta watershed outlet (NSE=0.66, RSR = 0.58, PBIAS = -10.8).

Figure 6. Map panels exhibiting the spatial distribution of GIWs simulated within: (A) Baseline; (B) Scenario 2; (C) Scenario 3; (D) Scenario 4; (E) Scenario 5; (F) Scenario 6.

Figure 7. Example simulated hydrographs. The first plot (A) shows a pair of high rainfall events on 21 March, 2001 and 30 March, 2001. The 21 March event is the highest rainfall event in the plot. Following this event, Baseline simulations exhibit an average daily peak volumetric streamflow rate approximately $3 \text{ m}^3 \text{ s}^{-1}$ less than that of Scenario 1 (100% GIW removal). The 30 March event is the smaller rainfall event for which the Baseline exhibits an average daily peak

volumetric streamflow rate approximately $1.24 \text{ m}^3 \text{ s}^{-1}$ less than that of Scenario 1. The second plot (B) shows a small rainfall event and subsequent days for which the Baseline simulated average daily streamflow returns to a baseflow volumetric rate approximately $0.32 \text{ m}^3 \text{ s}^{-1}$ greater than that simulated by Scenario 1 (100% GIW removal).

Figure 8. Exceedance probability distribution for Baseline and Scenario 1 (100% GIW removal) simulations.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

A. **Figure 6**

B.

C.

D.

E.

F.

■ Simulated GIW □ Nahunta Boundary

0 9.5 Kilometers

Figure 7

Figure 8