WATERSHED SCALE NITRATE-N ABATEMENT OF INSTREAM WETLANDS: AN APPRAISAL USING THE SOIL AND WATER ASSESSMENT TOOL

D. C. Sohoulande Djebou, A. A. Szogi, K. C. Stone, J. M. Novak

HIGHLIGHTS

- SWAT used to address watershed scale nitrate-N abatement of instream wetlands (ISWs).
- Experimental ISW results were incorporated into the watershed modeling framework.
- SWAT successfully captured and reproduced ISW impact on nitrate-N at sub-basin level.
- Scenarios of ISWs implementation were simulated, effects on nitrate-N export were evaluated.
- Results show ISWs can be used as conservation structures aimed at enhancing water quality.

ABSTRACT. *In watersheds under high agricultural production, nitrate nitrogen (nitrate-N) pollution often originates from intensive application of fertilizers and animal manure to croplands. Surface runoff and nitrate-N export from farmlands contributes to the pollution of nearby reaches which flow into the watershed stream network. Experimental studies reported significant nitrate removal capacities of constructed instream wetlands (ISWs). However, cases of large-scale implementations of ISWs are uncommon, probably due to a paucity of watershed-scale studies which highlight the influence of ISWs on riverine water quality. To elucidate the ISWs nitrate-N abatement potential at the watershed scale, the Soil and Water Assessment Tool (SWAT) was used to model nitrate-N export in a highly agricultural watershed located in the Coastal Plain of North Carolina. SWAT was first calibrated and validated for streamflow and for nitrate-N export using data collected from the inlet and outlet of an experimental instream wetland. The validated SWAT model was used to simulate a decade of nitrate-N export under two scenarios: 1) watershed with ISWs implemented; and 2) watershed without ISWs. The results of the case study indicated that a watershed-wide implementation of ISWs is likely to curtail annual nitrate-N export by 49%. The study also evaluated cases where ISWs are implemented in selected percentage of sub-basins across the watershed. The outcomes show higher increments of nitrate-N curtailment when ISWs are implemented in the first top agricultural sub-basins. Hence, implementation of ISWs on selected sub-basins can mitigate nitrate-N from non-point sources and enhance water quality in the watershed's stream network.*

Keywords. *Runoff, Croplands, Instream wetland, Nitrate-N export, Denitrification, SWAT model, Watershed.*

Worldwide, N fertilizers are by far the most used nutrients in agriculture (FAOSTAT, 2019). During the decade 2007 to 2016, the annual use of N fertilizers has increased by 13% justifying the rapid expansion of fertilizer-use observed across the globe (Jankowski et al., 2018; FAOSTAT, 2019). Nitrogen fertilization is applied to crops and pastures in either organic (e.g., manure, urea) or inorganic forms (e.g., ammonium sulfate, diammonium phosphate, potassium nitrate). Organic N forms applied to soil are not available to plants until they mineralize and release ammonium (NH_4^+) which can further be transformed to nitrate (NO_3^-) via nitrification (Canter, 1997; Kuypers et al., 2018). An overuse of N in the form of nitrate has been reported to occur in many farmlands across the United States (Swaney et al., 2018). Often, a fraction of the nitrate-N applied to soil is exported through sub-flow and surface runoff toward the nearby water bodies where excess nitrate can lead to water quality impairment. Indeed, the excess of nitrate in freshwater bodies is a threat for humans, animals, and aquatic life (Carlson 2018). In addition, N pollution of water resources has become a major concern in the United States as both N fertilizers and manure are often applied beyond assimilative capacity of plants and soils (Burkholder et al., 2006; Swaney

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et al., 2018). This situation warranted research initiatives aimed to curtail nitrate export from agricultural lands.

At the watershed scale, cases of waterbody impairments are often ascribed to the nitrate originating from nonpoint sources such as agricultural lands. Hence, many studies have evaluated alternatives to mitigate nonpoint source nitrate pollution. Among these alternatives are the instream wetlands. Instream wetlands (ISWs) were investigated and reported to have significant nitrate abatement potential (Hunt et al., 1999; Stone et al., 2004; Novak et al., 2012). Individually, wetlands are natural ecosystems known to remove meaningful amounts of riverine nitrate (Hansen et al., 2018). ISWs are designed to leverage the denitrification potential (i.e., bacterial reduction of nitrate NO_3 to N_2 or N_2O gases) of natural wetlands (Scholz et al., 2007). ISWs are often designed and constructed at locations naturally propitious such as floodplains or marshes (Stone et al., 2003; Hunt et al., 2014; Kasak et al., 2018). When constructed, an ISW intercepts and retains runoff water temporarily before it flows into the stream-network. As the runoff water is retained in the ISW under anaerobic conditions, microbial denitrification takes place leading to a curtailment of the nitrate loading (Rivett et al., 2008; Novak et al., 2012). Up to date, several studies evaluated and quantified the denitrification process by monitoring experimental ISWs, but aspects related to a watershed scale implementation of the ISWs have not been sufficiently investigated. The objective of this study is to use a modeling approach to quantify ISWs nitrate abatement at the watershed scale. In fact, a watershed scale simulation of the ISWs is needed to appraise the scalability of experimental results on ISWs nitrate curtailment. Hence, this study uses the Soil and Water Assessment Tool (SWAT) to model nitrate-N export in the Northeast Cape Fear River watershed in North Carolina. The Northeast Cape Fear River watershed encompasses many sub-basins (i.e., sub-watersheds) among which is the Herrings Marsh Run (HMR) catchment. During the period 1991 to 2000, an experimental ISW was constructed and monitored by the United States Departments of Agriculture (USDA) in the HMR sub-basin (Stone et al., 2004). The experimental ISW data were integrated in the SWAT framework to simulate scenarios of nitrate-N export at the watershed scale. This article presents the analytical framework of the study as well as the major outcomes.

DATA AND METHOD

STUDIED WATERSHED

The study addressed nitrate-N (NO_3 - N) export in the Northeast Cape Fear River watershed located in the State of North Carolina, United States (fig. 1). The watershed is associated with the United States Geological Survey's Hydrologic Unit Code USGS' HUC 03030007 and is part of the Cape Fear River basin. The watershed has a total area of 1533.67 km^2 from which 86% is in the Duplin County, North Carolina. Duplin County is known for having an exposure to water quality issues due in part to the intensive swine and poultry production taking place across the county (Mallin et al., 2015). These animal production operations generate substantial quantities of manure rich in nutrients. The manures are often applied to croplands or hayfields as part of the farm's nutrient management plan. Croplands represent 41% of the Northeast Cape Fear River watershed area (fig. 1a and table 1). In table 1, the areal changes of land-cover classes were estimated for the watershed based on 2001, 2006, and 2011 national land-cover database (NLCD) developed by the Multi-Resolution Land Characteristics consortium (www.mrlc.gov) (Homer et al., 2015). The statistics summarized in table 1 show that the land cover classes distribution is mostly stable across the watershed during the period 2001 to 2011. These statistics also align with the ten years (2008 to 2017) average annual land-cover distributions available in the CropScape database. Note, the CropScape database is a platform developed by the USDA's National Agricultural Statistic Service (USDA-NASS) to provide year to year cropland data layers for the conterminous US (Han, 2012). In the case of the Northeast Cape Fear River watershed, the NLCD's land-cover distribution is overall consistent with CropScape data, but NLCD seems to underestimate pasture and hay areas probably due to the classification approach. The choice of the Northeast Cape Fear River watershed for this study, aligns with a series of research on instream wetlands conducted by the USDA's Agricultural Research Service in the HMR. The HMR is a sub-basin of 4.09 km^2 encompassed by the Northeast Cape Fear River watershed. Additional details regarding the HMR sub-basin will be presented in the next section.

EXPERIMENTAL INSTREAM WETLAND

The experimental ISW considered in the study was situated in the HMR sub-basin (fig. 2). Figure 2a shows the HMR sub-basin (4.09 km^2) within the Northeast Cape Fear River watershed. During the decade 1991 to 2000, the USDA conducted studies on nutrients exports in the HMR (Stone et al., 2004). Initially, the ISW site was a beavers' dam (see fig. 2d) on the HMR stream (Stone et al., 2004). Late in 1993, USDA reinforced the beavers' dam by constructing a levee to stabilize the water pond and enable nutrients load monitoring. The pond volume was estimated as 29000 m^3 (Novak et al., 2012) and it drained water from approximatively 409 ha. Figure 2c presents the configuration of the ISW which had two inlets and one outlet. An USGS station is also located at the outlet of the ISW. Thus, measurements of streamflow and nitrate-N loading were continuously collected at the inlet and outlet of the ISW. As reported in previous USDA studies the ISW played an important denitrification role and contributed significantly to the nitrate-N abatement (Stone et al., 2004). However, the performance of the ISW is also variable depending on the month of the year as warm months were reported with a high denitrification rate compared to cooler months (Hunt et al., 1999, Novak et al., 2012). Figure 3 recaps the monthly averages of the inflow and outflow nitrate-N loadings at the ISW. The graphs in figure 3 show higher nitrate-N abatements during the warm months of the year. The nitrate-N abatement contrast between warm and cold months is driven by the microbial activities in the ISW (Hunt et al., 1999; Stone et al., 2004; Novak et al., 2012). Indeed, the microbial activities are highly influenced by the ambient temperature and they

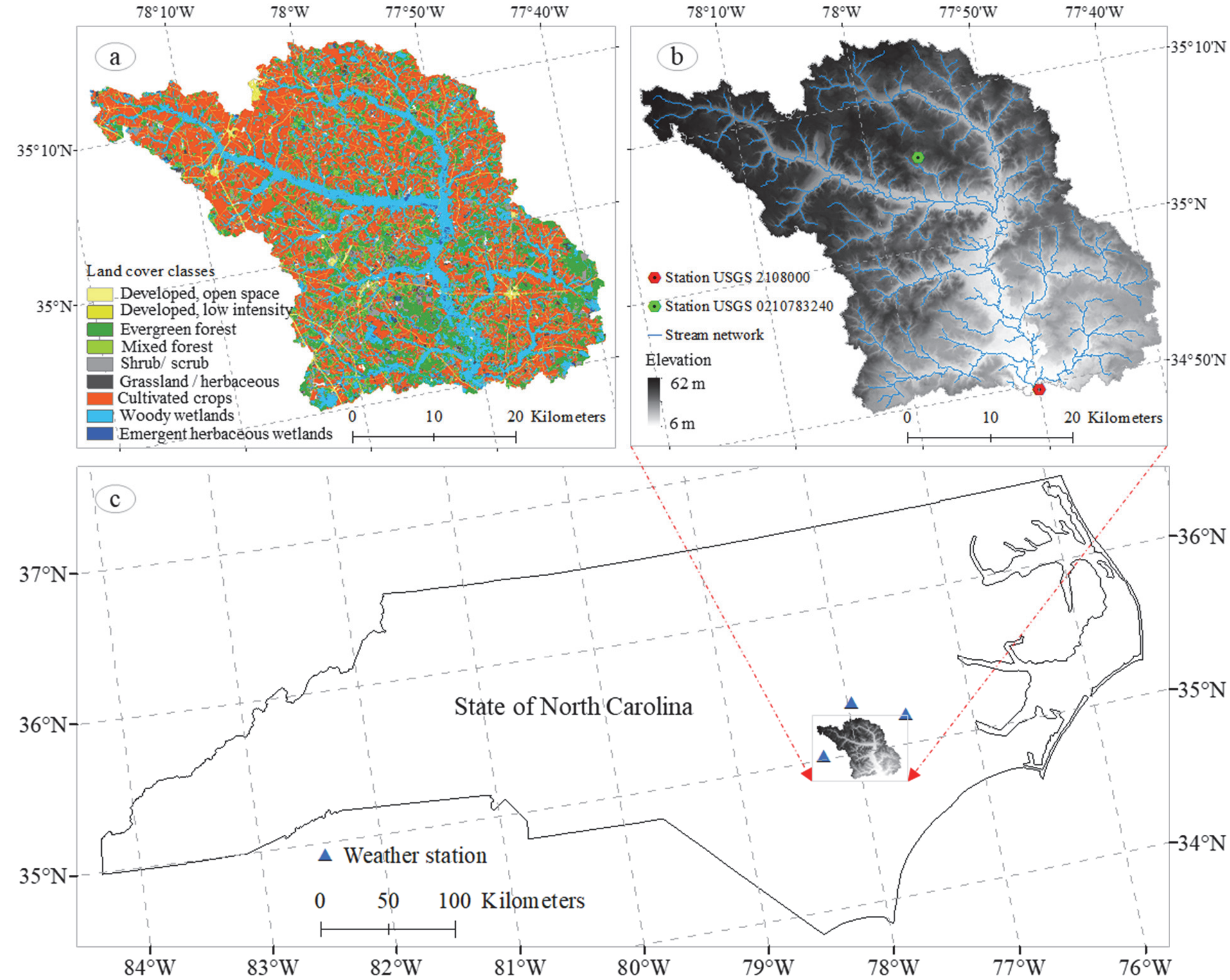


Figure 1. The upper Northeast Cape Fear River watershed as located in the State of North Carolina. (a) Presents the land cover distribution; (b) presents an overlay of the stream network on the digital elevation model, and (c) presents the watershed in the State of North Carolina.

are relatively slowed in colder weather (Hunt et al., 1999; Canion et al., 2014).

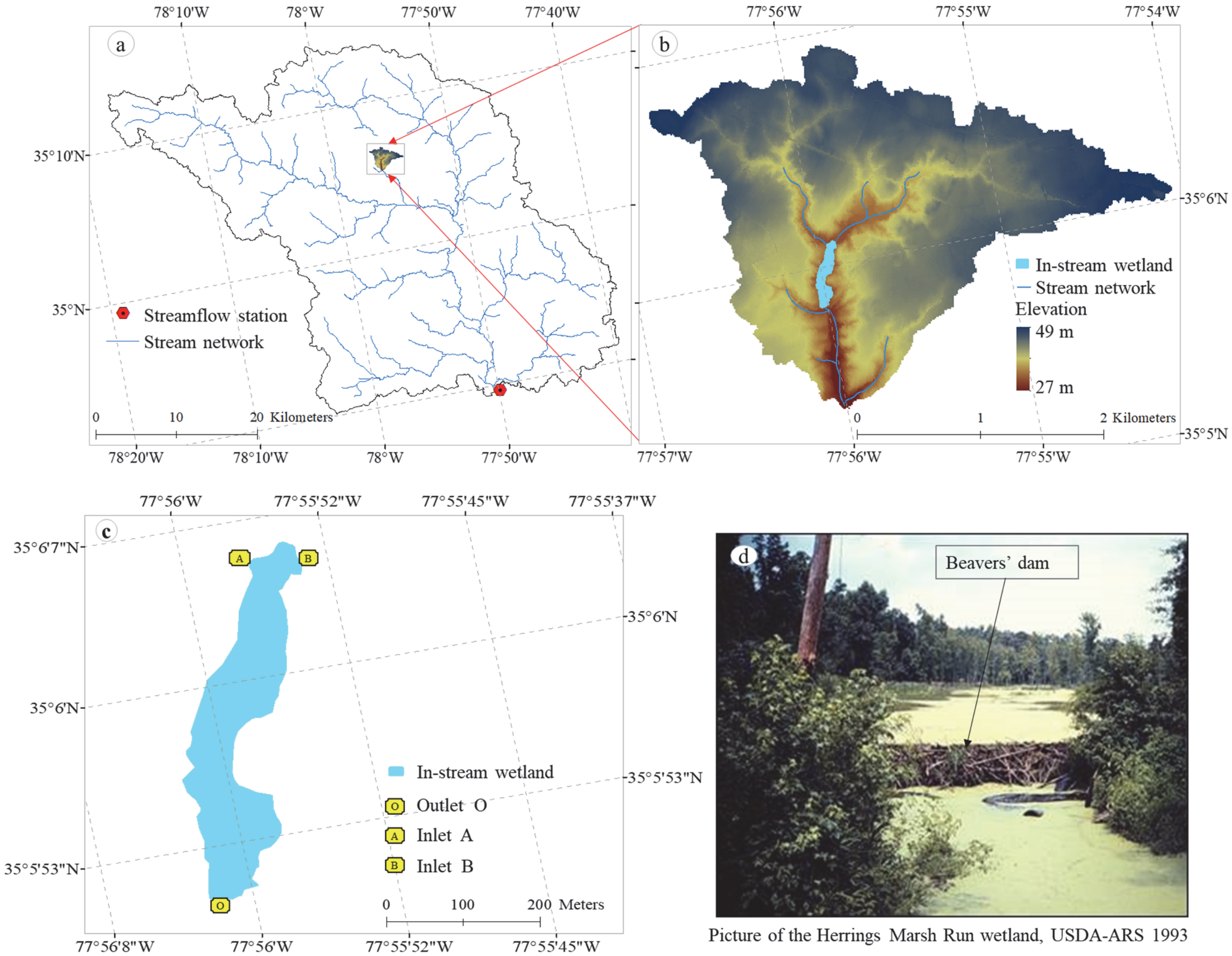
DATA DESCRIPTION

The study employed different categories of data including streamflow, nitrate-N loading, weather, and geo-spatial data. Monthly streamflow data were obtained from the USGS database for two streamgages. The first streamgage, referenced USGS-2108000, corresponds to the studied watershed's outlet in the Northeast Cape Fear River watershed. The second streamgage referenced USGS-0210783240 is located 30 m downstream of the ISW outlet in the Herrings Marsh Run

Table 1. Overview of land-cover distribution across the studied watershed during years 2001, 2006, and 2011.[a]

Land-Cover Classes		Total Area (ha)			Coverage (%)		
Code	Designation	2001	2006	2011	2001	2006	2011
11	Open water	478	478	484	0.31	0.31	0.32
21	Developed, open space	4887	4887	4889	3.19	3.19	3.19
22	Developed, low intensity	1501	1506	1508	0.98	0.98	0.98
23	Developed, medium intensity	188	204	206	0.12	0.13	0.13
24	Developed, high intensity	45	55	55	0.03	0.04	0.04
31	Barren land	5	409	385	0.00	0.27	0.25
41	Deciduous forest	336	321	311	0.22	0.21	0.20
42	Evergreen Forest	23036	20508	18636	15.02	13.37	12.15
43	Mixed forest	6340	5728	5330	4.13	3.73	3.48
52	Shrub/ scrub	17166	17463	19143	11.19	11.39	12.48
71	Grassland/ herbaceous	2771	5216	5861	1.81	3.40	3.82
81	Pasture/ hay	224	218	218	0.15	0.14	0.14
82	Cultivated crops	63607	63580	63550	41.47	41.46	41.44
90	Woody wetlands	31532	30963	30383	20.56	20.19	19.81
95	Emergent herbaceous wetlands	1249	1831	2407	0.81	1.19	1.57
Total		153367	153367	153367	100.00	100.00	100.00

[a] Land-cover distribution statistics are retrieved from the NLCD 2001, 2006, and 2011 developed by the Multi-Resolution Land Characteristics consortium (MRLC) (Homer et al., 2015).



Picture of the Herrings Marsh Run wetland, USDA-ARS 1993

Figure 2. Overview of the studied watershed encompassing the instream wetland. (a) The upper Northeast Cape Fear River watershed, (b) the Herrings Marsh Run sub-basin, (c) the in-stream wetland, (d) a 1993 picture showing the beavers' dam at Herrings Marsh Run wetland.

sub-basin. The streamflow data were used to calibrate and validate the SWAT simulations of runoff. As runoff causes nutrients export, an accurate flow simulation is essential to achieve reasonable nitrate-N export. The nitrate-N data used in the study are those collected at the inlet and outlet of the experimental ISW. As presented in figure 2c, runoff and nitrate-N inflow into the wetland at two inlets A and B, then outflow through the outlet O. To simplify the nitrate-N modeling, the quantities of nitrate-N inflow and outflow were calculated and thereafter used in the study. Hence, the observed inflow nitrate-N ($Nitrate_{Inlet}$) and the outflow nitrate-N ($Nitrate_{Outlet}$) were obtained using the equations 1 and 2:

$$Nitrate_{Inlet} = C_A q_A + C_B q_B \tag{1}$$

$$Nitrate_{Outlet} = C_{Outlet} q_{Outlet} \tag{2}$$

where C_A, C_B, C_{Outlet} are the measured nitrate-N concentrations at inlet A, inlet B, and outlet O, respectively. Likewise, q_A, q_B, q_{Outlet} are the monthly flows at inlet A, inlet B, and outlet O, respectively.

The ISW data were used to calibrate and validate the SWAT simulations of the nitrate-N export. Additional details on the streamflow and nitrate-N data are summarized in table 2. Note, the modeling's timeline spans the period 1990 to 2017 and it consists of time slices which will be further described in the method section. Historical weather data in-

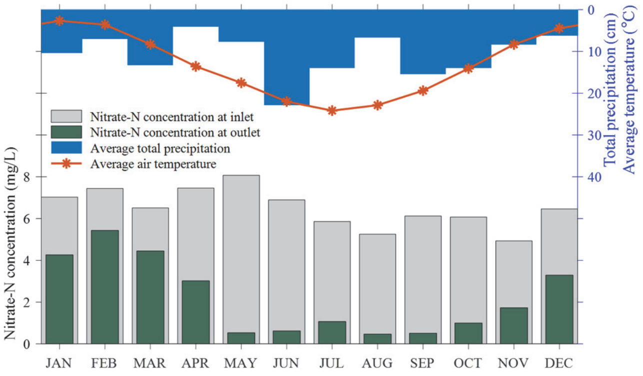


Figure 3. Overview of the nitrogen abatement performance of the experimental Herrings Marsh Run's instream wetland (ISW). Monthly averages of Nitrate-N are calculated based on the USDA measurements during the period 1994 to 1997 (Hunt et al., 1999); monthly temperature and precipitation curves are derived from NOAA weather stations data.

cluding daily precipitation and daily maximum and minimum air temperature of three neighboring weather stations were obtained from the National Oceanic and Atmospheric Administration (NOAA) database. The three stations are located at the vicinity of the Northeast Cape Fear River watershed and they are referenced by NOAA as USC00311881 (latitude 35.02 and longitude -78.28), USC00314684 (latitude 35.19 and longitude -77.54), and USW00013713 (latitude 35.34 and longitude -77.96). At each station, daily precipitation and air temperature data were retrieved for the period 1990 to 2017 and used at different stages of the SWAT modeling. The study also used geo-spatial data including a digital soil map data retrieved from the State Soil Geographic database (STATSGO), 30 m digital elevation model (DEM) released by the U.S. Geological Survey (USGS), and 30 m land use land cover (LULC) data for years 2001, 2006, and 2011 developed by the by the Multi-Resolution Land Characteristics (MRLC) consortium (www.mrlc.gov) (Homer et al., 2015). The 2001, 2006, and 2011 LULC were used for the LULC change analysis reported in table 1. However, this analysis showed no major LULC change for the watershed, hence the 2011 LULC was used as SWAT input. The STATSGO soil map developed by the National Cooperative Soil Survey of the United States Department of Agriculture (USDA) (www.nrcs.usda.gov), consists of a georeferenced inventory of soils with attributes data describing the properties. The use of STATSGO dataset in SWAT is recommended when the simulated watershed is relatively large and the temporal resolution is monthly (Geza and McCray, 2008; Mukundan et al., 2010; Sohoulande, 2019). In the present study, STATSGO was used to reduce the computational burden due to the relatively large size of Northeast Cape Fear River and the monthly simulation considerations.

SWAT MODEL CALIBRATION AND VALIDATION

The study exploited the capacity of the SWAT model to reproduce the hydrologic behavior of the Northeast Cape Fear River watershed (fig. 1). As nutrients export strongly depends on water flow, SWAT was employed to simulate streamflow and nitrate-N export at the watershed scale. Explicitly, the modeling approach involved two stages as SWAT was first calibrated and validated for streamflow using observed data at the Northeast Cape Fear River's stream gage (USGS 2108000), thereafter for nitrate-N export using the experimental ISW data.

Table 2. Overview of data availability at the stream gages considered for SWAT modeling.

		Watershed/ Sub-basin	
		Northeast Cape Fear River	Herrings Marsh Run
Streamgage reference		USGS 2108000	USGS 0210783240
Latitude		34.83°	35.10°
Longitude		-77.83°	-77.93°
Elevation		5.27 m	28.96 m
Location		Duplin, N.C.	Duplin, N.C.
Hydrological unit code		3030007	30300070206
USGS drainage area		1551.4 km^2	3.86 km^2
SWAT delineated area		1533.67 km^2	4.09 km^2
Data availability	Flow	1940 to 2018	1991 to 2000
	NO_3-N ISW inlet	NA	1993 to 1997
	NO_3-N ISW outlet	NA	1993 to 1998

During the first stage, the streamflow was calibrated and validated for the monthly periods 1994 to 1996 and 1997 to 2000 respectively. Hence, ArcSWAT (Neitsch et al., 2011) was set using the afore-described weather and geo-spatial data of the Northeast Cape Fear River watershed. To define the streams network and sub-basins, a DEM-based watershed delineation option was used along with an upstream area threshold of 200 ha. Following this procedure, sub-basins were created automatically. The sub-basin comprising the experimental ISW was manually edited to match the streamgage USGS 0210783240. Multiple hydrologic response units (HRUs) were defined by specifying 5% thresholds for land use percentage, soils classes, and slope. Note, the HRU is the functional hydrologic unit of the SWAT model and each sub-basin encompasses a variable number of HRUs (Neitsch et al., 2011). The calibration procedures were both automatic and manual. Indeed, the streamflow was calibrated using the SWAT's calibration and uncertainty programs (SWAT-CUP) which is an automatic calibration extension of SWAT (Abbaspour 2013). The autocalibration is an iterative procedure and the built-in SUFI-2 algorithm of SWAT-CUP was used. SUFI-2 enables the sensitivity analysis of SWAT parameters and narrows down bias in simulations by identifying the parameter ranges that leads to reasonable model performance (Abbaspour, 2013). The performance criteria selected for the SUFI-2 application was the Nash-Sutcliffe's Efficiency NSE with 0.5 as a minimum threshold. The procedure facilitates the calibration and validation of the SWAT model for streamflow in Northeast Cape Fear River. As the SWAT model simulates streamflow at the watershed scale, the output database also provides detailed simulations for each sub-basin. Hence, for the validation period 1997 to 2000 the outputs of the HMR sub-basin were retrieved for comparison with the observed flow data at the stream gage USGS-0210783240.

During the second stage, the calibrated model for streamflow was used to set separately two scenarios of nitrate-N export including a scenario with ISWs implemented across the watershed, and a scenario with no ISW implemented. Hence, the monthly period 1994 to 1995 and 1996 to 1998 were considered for the nitrate-N calibration and validation, respectively as data availability permitted. In the procedure, the HMR sub-basin was targeted and Nitrate-N loading data at the outlet of the experimental ISW were used to calibrate the model under the scenario where ISWs are implemented. Antagonistically, the Nitrate-N loading data at the inlet of the experimental ISW were used to calibrate the model under the scenario without ISWs. Following the nitrate exports validation in the HMR sub-basin, the parameter sets were considered for the two nitrate-N export scenarios (i.e. watershed with ISWs implemented, watershed without ISW).

During both streamflow and nitrate-N simulations, a one year warming period was considered in ArcSWAT. The parameters involved in the calibrations, were selected in accordance with previous studies which outlined the most sensitive SWAT parameters based on the modeling objectives (White and Chaubey, 2005; Arnold et al., 2012; Teshager et al., 2016). For instance, the parameters adjusted for streamflow included the Soil Conservation Service runoff curve number at moisture II (CN2), the soil available water capacity (SOL_AWC), and the saturated hydraulic conductivity (SOL_K). To achieve SWAT calibration for nitrate-N export, management inputs such as the management operation (MGT_OP), fertilizer identification number (FERT_ID), and fertilizer application (FRT_KG) were modified for croplands in the SWAT database (Neitsch et al., 2011). Owing to the large size of the watershed and the difficulty to integrate into the model the broad nature of farm management practices (e.g., crop rotations, tillage types, nutrient managements, irrigation, soil and water conservation), assumptions were made. Especially, the study assumed an early fall conservation tillage (TILLAGE_ID=3) and a nitrogen fertilization in term of urea (FRT_ID = 4) up to 200 kg N/ha for the croplands during all the years of simulation. The agricultural Land-row crops (AGRR) was assumed for the croplands and it uses values for corn (Arnold et al., 2013). The SWAT setting also assumes that the essential part of the nitrate originates from croplands which are often the major non-point sources of nutrients in agricultural landscapes (Conway and Pretty, 2013). The parameters adjusted during the manual calibration included denitrification threshold water content (SDNCO), denitrification exponential rate coefficient (CDN), nitrate percolation coefficient (NPERCO), and nitrogen uptake distribution parameter (N_UPDIS). The parameters SDNCO and CND allow to control the rate of denitrification in SWAT model. NPERCO and N_UPDIS helped to adjust the nitrate lost through percolation and the nitrate uptake by the vegetation covers. Table 3 summarizes the adjusted parameters.

EFFICIENCY ANALYSIS

The performance of SWAT at simulating streamflow and nitrate-N export were evaluated during the calibration and validation phases. Four indicators of model performance were calculated including the Nash-Sutcliffe's Efficiency NSE (eq. 3), the index of agreement d_1 (eq. 4), the coefficient of determination R^2, and the Root Mean Squared Error RMSE (eq. 5) (Arnold et al., 2012).

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(q_i - q_i'\right)^2}{\sum_{i=1}^{n}\left(q_i - \overline{q}\right)^2} \qquad (3)$$

$$d_1 = 1 - \frac{\sum_{i=1}^{n}\left|q_i' - q_i\right|}{\sum_{i=1}^{n}\left(\left|q_i' - \overline{q}\right| + \left|q_i - \overline{q}\right|\right)} \qquad (4)$$

$$RMSE = \left[n^{-1}\sum_{i=1}^{n}\left(q_i - q_i'\right)^2\right]^{0.5} \qquad (5)$$

where q_i and q_i' are respectively the observed and simulated values (i.e. monthly streamflow or nitrate-N export) at time i, $\overline{q}$ is the average of the observed values, n is the number of months during the calibration or validation period.

Following the calibration and validation of the SWAT model, 10-year simulations of nitrate-N export were carried out over the period 2008 to 2017. The period 2008 to 2017 is arbitrary chosen to illustrate the watershed scale pattern of a recent decade. The simulations were conducted for two scenarios including a scenario where ISWs are implemented across the watershed and an antagonistic scenario with no ISW implemented. When the SWAT model simulates nitrate-N export at the watershed scale, the output database also provides detailed simulations for individual sub-basins across the watershed. This allows to quantify the nitrate-N export for individual sub-basins. Hence, under the scenario with ISWs, cases of partial implementations of ISWs were also evaluated by assuming the presence of ISWs in the top 10%, 20%, …, 90% of the highly agricultural sub-basins selected across the watershed. Note, to define the top highly agricultural sub-basins, the percentage of croplands in each sub-basin were estimated then ranked. For each case of partial ISWs implementation, the corresponding watershed scale nitrate-N curtailments were estimated. The outcomes were compared and the potential nitrate abatement of a watershed scale implementation of ISWs was discussed.

RESULTS

STREAMFLOW AND NITRATE-N EXPORT

During the SWAT modeling of the Northeast Cape Fear River watershed, a total of 447 sub-basins were delineated among which is the HMR sub-basin. The model was sucessfully calibrated and validated for streamflow at the watershed's outlet (i.e., streamgage USGS 2108000). Figure 4 presents a comparaison of both observed and

Table 3. Summary of the SWAT model parametrization.

Parameter	Description	Default Range	Range/value Used at Calibration and Validation	
			With ISWs	Without ISWs
CN2	Soil Conservation Service runoff curve number for moisture condition II	35-98	25-92[a]	25-92[a]
SOL_AWC	Soil available water capacity	0-1	0.05-0.46[a]	0.05-0.46[a]
SOL_K	Saturated hydraulic conductivity	0-2000	51-1155[a]	51-1155[a]
SDNCO	Denitrification threshold water content	0-1	0.8[b]	1.1[b]
CDN	Denitrification exponential rate coefficient	0-3	2.4[b]	0.8[b]
NPERCO	Nitrogen percolation coefficient	0-1	0.1[b]	0.2[b]
N_UPDIS	Nitrogen uptake distribution parameter	0-100	30[b]	10[b]

[a] Values vary depending on the HRU.

[b] Values at basin level.

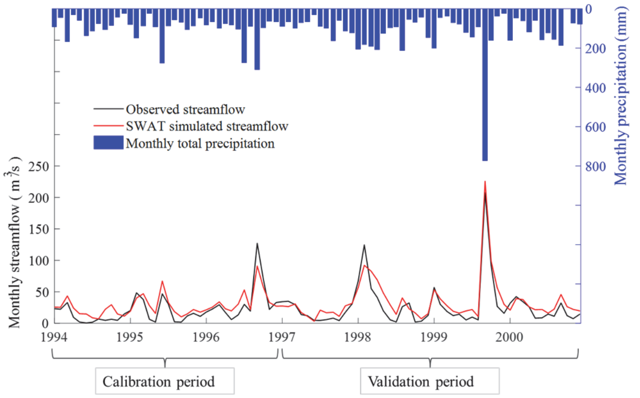


Figure 4. Comparing observed versus simulated streamflow during SWAT model calibration and validation at the Northeast Cape Fear River's streamgage (USGS 2108000).

simulated streamflow during the calibration and validation of the model. The efficiency values summarized in table 4 sustain the ability of SWAT to reproduce the hydrology behavior of the watershed (e.g. calibration NSE=0.70, validation NSE=0.85). For the validation period, the SWAT simulation of streamflow at the HMR sub-basin was retrieved and compared to the observed flow at the streamgage USGS 0210783240. Figure 5 recaps this comparison between simulated and observed flow at the HMR's outlet. The corresponding efficiency values in table 4 are acceptable (NSE=0.83, d_l≥0.71, R^2≥0.90). This result indicates that while SWAT simulates flow for the Northeast Cape Fear River watershed, it also reproduces well the flow at the sub-basin level.

As described in the method section, SWAT Nitrate-N export was calibrated and validated using the data recorded from the ISW. Two scenarios of SWAT setting were developed. The first scenario assumed a watershed-wide implementation of ISWs with similar nitrate-N abatement potential as the HMR's experimental ISW (see fig. 3). The second scenario of SWAT setting assumes no ISW implemented watershed-wide. For the first scenario, SWAT nitrate-N simulation at the HMR's sub-basin was set using the observed nitrate-N export at the experimental ISW's outlet. In contrast, the second scenario of SWAT was set using the observed nitrate-N export at the experimental ISW's inlet. Table 5 reports the efficiency analysis of the SWAT simulation of nitrate-N export at the HMR's sub-basin level. The efficiency values obtained for SWAT nitrate-N export calibration (NSE≥0.78, d_l≥0.69, R^2≥0.70) and validation (NSE≥0.61, d_l≥0.58, R^2≥0.70) are acceptable for both ISW's inlet and outlet conditions (Arnold et al., 2012, White and Chaubey, 2005). The SWAT settings were henceforth used to simulate a 10-year nitrate-N export at the watershed scale.

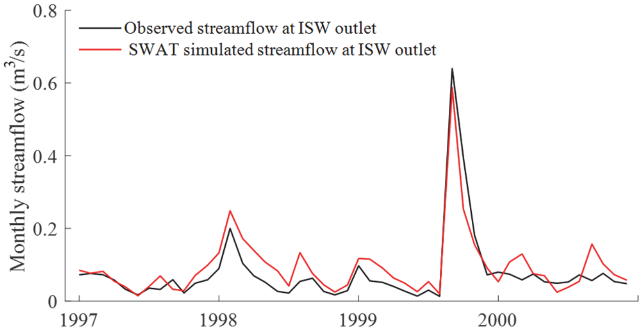


Figure 5. Comparing SWAT flow simulation to the measured flow at the Herrings Marsh Run's ISW outlet (USGS 0210783240) during the validation period (1997 to 2000).

Table 4. Efficiency estimates for SWAT simulation of streamflow at the Northeast Cape Fear River and the Herrings Marsh Run watersheds.

		Northeast Cape Fear River		Herrings Marsh Run
		Calibration (1994-1996)	Validation (1997-2000)	Validation (1997-2000)
Efficiency criteria	NSE	0.70	0.85	0.83
	d_l	0.67	0.74	0.71
	R^2	0.80	0.90	0.90
	RMSE	13.03	15.66	0.05

Table 5. Efficiency estimates for SWAT simulation of Nitrate-N export using experimental ISW inlet and outlet conditions.

		Nitrate-N Export (ISW Inlet's Condition)		Nitrate-N Export (ISW Outlet's Condition)	
Period		Calibration	Validation	Calibration	Validation
Efficiency criteria	NSE	0.78	0.63	0.80	0.61
	d_l	0.70	0.58	0.69	0.65
	R^2	0.78	0.70	0.81	0.76
	RMSE	0.74	0.59	0.50	0.57

WATERSHED SCALE NITRATE-N ABATEMENT

As mentioned earlier in the sections above, the SWAT settings were used to simulate 10-year monthly nitrate-N export for the Northeast Cape Fear River. Figure 6 recaps the cumulative nitrate-N export under the afore-described scenarios including the scenario with a watershed-wide implementation of ISWs and the scenario with no ISW implemented. The cumulative nitrate-N exports are reported by unit watershed area in figure 6a and by unit croplands area in figure 6b. Overall, figure 6 indicates that the watershed-wide implementation of ISWs, would contribute to abate the total nitrate-N export by 49%. Over the decadal period 2008 to 2017, this will equate to a denitrification of 60.18 kg of nitrate-N per hectare of watershed area. The equivalent denitrification amount could also be evaluated as 147 kg of nitrate-N per ha of croplands. However, the magnitude of denitrification is not the same from one month to another as shown by figure 7. Indeed, figure 7 present the month-to-month average nitrate-N exports reported to the entire watershed area (fig. 7a) and the croplands only (fig. 7b). The ISWs nitrate-N removal rate is the difference of nitrate-N export between the two scenarios simulated (i.e., watershed without ISWs and watershed with ISWs). The peak of ISWs nitrate-N removal is observed during the month July with an average of 3.28 kg of nitrate-N per hectare of cropland, while the lower rate is observed during the month of January with an ISWs nitrate-N removal rate of 0.21 kg of nitrate-N per ha of cropland.

While the results presented by figure 6 assumed ISWs were implemented in the 447 sub-basins delineated within the Northeast Cape Fear River watershed, the study also included evaluation of cases of partial implementations of

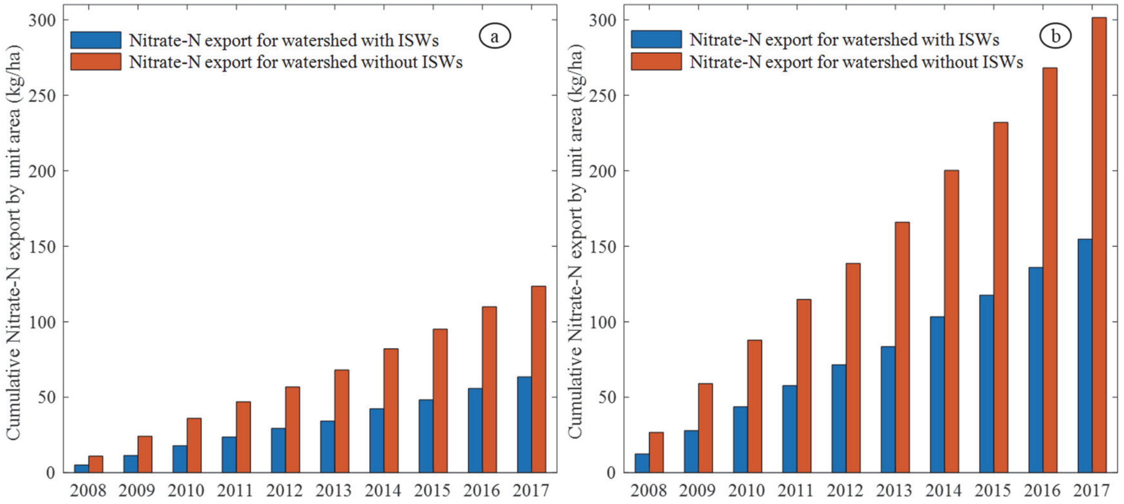


Figure 6. Comparing a 10-year cumulative Nitrate-N export simulated under a condition where ISWs are implemented across the watershed versus no ISWs implemented. (a) Shows the nitrate-N exports per ha of watershed area, (b) shows the nitrate-N exports per ha of croplands.

ISWs. Thus, table 6 summarizes the watershed scale nitrate-N curtailment when ISWs are implemented in the top 10%, 20%, …, 90% of the highly agricultural sub-basins. The estimates show higher increments of nitrate-N curtailment when ISWs are implemented in the top highly agricultural sub-basins. For instance, implementing ISWs in the top 10% of the sub-basins would abate the nitrate-N export by 12 kg/ha which also corresponds to 20% of the total nitrate-N abatement if ISWs were implemented in all the sub-basins. Likewise, the results in table 6 show an equal nitrate-N abatement performance for both cases of 90% and 100% ISWs implementation.

SYNTHESIS AND DISCUSSION

In natural ecosystems, wetlands play a critical role in the provision of clean water (Janse et al., 2019). Clean water is vital for the aquatic life, but also to human, plant and animal communities. Unfortunately, freshwater quality impairment has become an issue in many watersheds as human activities intensify. Important quantities of nitrate are frequently exported from farmlands toward stream networks especially in highly agricultural landscapes (Rivett et al., 2008). At the watershed scale, the nitrate originating from agricultural lands (diffuse sources) are difficult to control. However, implementing ISWs is worthy of consideration, because of their high denitrification potential (Hunt et al., 1999; Novak et al., 2012). Hence, this study uses a hydrological modeling approach to provide insights into the nitrate-N curtailment of a watershed scale implementation of ISWs. The SWAT model was used to simulate the hydrologic behavior of the Northeast Cape Fear River watershed. The analysis of SWAT performances during the calibration and validation stages, suggested acceptable streamflow and nitrate-N export simulations. The SWAT model was thereafter used to simulate 10-year nitrate-N export under two scenarios in the Northeast Cape Fear River watershed. The first scenario assumed an implementation of ISWs in the sub-basins of the watershed, and the second scenario assumed no implementation of ISW. While denitrification processes are natural,

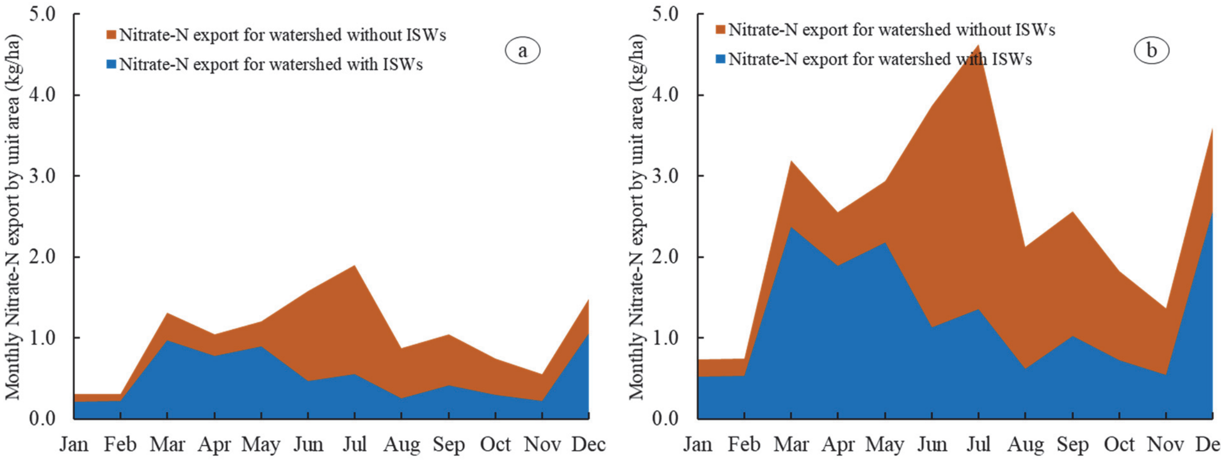
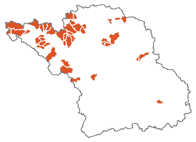
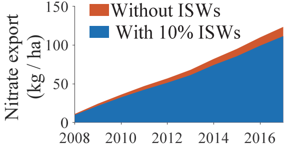
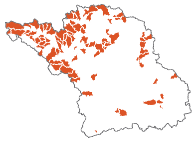
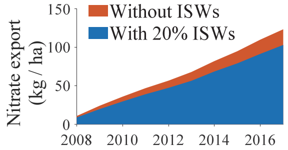
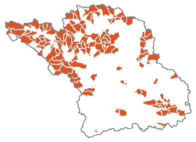
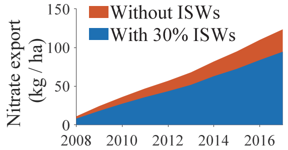
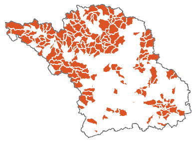
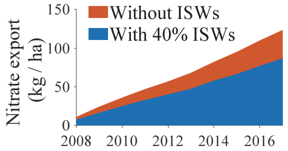
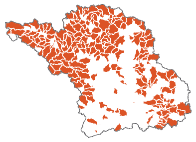
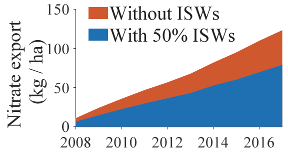
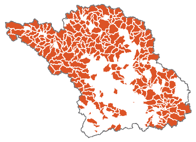
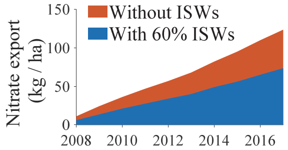
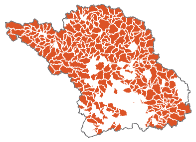
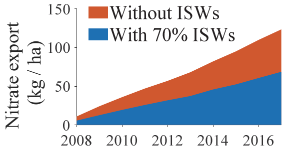
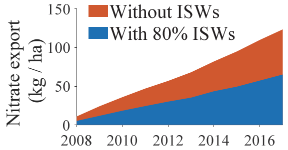
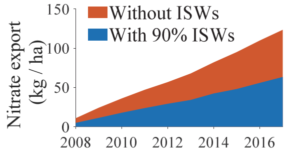
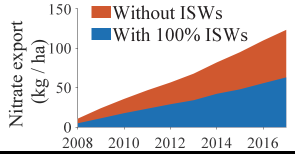


Figure 7. Comparing the average monthly Nitrate-N export based on SWAT simulations for 10-year period 2008 to 2017 under a condition where ISWs are implemented across the watershed versus no ISWs implemented. (a) Shows the nitrate-N exports reported to watershed area, (b) shows the nitrate-N exports reported to croplands.

Table 6. Evaluating the watershed scale nitrate curtailment when ISWs are implemented in a given percentages of sub-basins.[a]

Percentage Sub-Basins with ISWs	Sub-Basins Distribution	Watershed Scale Nitrate-N Export	Cumulative N Curtailment	Increment
10%			12.02 kg/ha	12.02 kg/ha
20%			20.45 kg/ha	8.43 kg/ha
30%			28.87 kg/ha	8.42 kg/ha
40%			36.70 kg/ha	7.83 kg/ha
50%			44.53 kg/ha	7.83 kg/ha
60%			49.95 kg/ha	5.42 kg/ha
70%			54.77 kg/ha	4.82 kg/ha
80%			58.38 kg/ha	3.61 kg/ha
90%			60.12 kg/ha	1.74 kg/ha
100%			60.18 kg/ha	0.06 kg/ha

[a] 447 sub-basins were delineated across the watershed and for each percentage, the sub-basins selected are highlighted in maroon.

the implementation of ISWs is likely to amplify the phenomenon and subsequently curtail the quantity of nitrate released into the stream network which is the outcome of the analysis of these two scenarios recapped in figure 6. Indeed, an analysis of the 10-year SWAT simulations shows that a watershed-wide implementation of ISWs would abate nitrate-N export into the stream network by 49%. However, cases of partial implementation of ISWs were evaluated and reported in table 6. The estimates show higher increments of the watershed scale nitrate-N abatement when the top percentages of agricultural sub-basins are selected for ISWs implementation. This later result sounds relevant as it could be used to elaborate a cost efficiency strategy for a watershed-wide

ISWs implementation. Although the case reported is associated to the Northeast Cape Fear River watershed, the results provide meaningful insights into the watershed-scale performance of ISWs.

The added value of this study is that the findings can contribute to the valorization of water quality protection through a development of water quality trading (e.g., nitrogen credit) (Gross et al., 2008; Kragt and Robertson, 2014). Specially, the ability of SWAT model to quantify the denitrification potential of ISWs at the watershed scale may be used to evaluate nitrogen credits (Gross et al., 2008). However, the denitrification efficiency of ISWs are variable over the year as warm months experienced higher nitrate-N curtailment compared to cold months (fig. 7). Therefore, the annual median value of less than 0.79 ppm reported for the U.S. Environmental Protection Agency's Coastal Plains Ecoregion (USEPA, 2000) is not being attained year-round (fig. 3). This is particularly true for parts of the Coastal Plains ecoregion with high population densities or high concentration of animal production operations and heavy use of fertilizers in croplands such as the North Cape Fear Basin (Omernik et al., 2016). Yet, other strategies should be considered to further abate the N footprint in sub-watersheds with intense animal swine and poultry production along with the implementation of ISWs. These additional strategies include the use of alternative methods to land application of animal waste known to significantly decrease the excess N at the farm scale such as manure nutrient transfer programs, thermal treatment of poultry litter or on-farm advanced treatment of liquid swine manure (Szogi et al., 2015; Vanotti et al., 2018; Bauer et al., 2019). However, the location choice for ISWs may emphasize a landscape balance approach as Ssegane and Negri (2016) used SWAT simulations to show that a sustainable configuration of landscape could reduce nitrate exports from farmlands. Hence, future research direction could be the use of SWAT simulations to identify site-specific inputs needed for the design and cost efficiency evaluation of ISWs.

CONCLUSIONS

Experimental in-stream wetland data were used in SWAT to model nitrate-N export under two scenarios including watersheds with ISWs and without ISWs. Cases of partial implementations of ISWs were also evaluated for their impact on the watershed scale nitrate-N curtailment. The case study of the Northeast Cape Fear River watershed shows that a watershed-wide implementation of ISWs would reduce by half the total nitrate-N loading in the stream network. Within the yearly period, high ISWs nitrate-N removal rates were associated to warm months (e.g., June, July), and low rates to cold months (e.g., January, February). The study also provides meaningful insights into the nitrate-N abatement patterns when ISWs are partially implemented across the watershed. The importance of the results reported in the study goes beyond the case study as it shows the capacity of using SWAT model to evaluate the large-scale effect of ISWs on nitrate-N control. Overall the outcomes of the study corroborated that:

- ISWs have a critical buffer role at controlling nitrate-N export from agricultural landscapes.
- SWAT can be used to portend nitrate-N abatement at the watershed scale when selected sub-basins are considered for the ISWs implementation.
- SWAT evaluation of ISWs may help quantify and establish a month by month nitrate credits to sustain a watershed scale water quality trading.

Although the modeling approach reported may lay the grounds to practical use of SWAT for ISWs evaluation, the study did not address questions related to the cost efficiency of ISWs implementation nor the inclusion of point-source nitrate-N discharges. In addition, the SWAT simulations assumed an adjustment of the denitrification parameters based on HMR data. In view of these drawbacks, further contributions on the subject could develop an approach to pinpoint sub-basins with high need of ISWs implementation and address their cost efficiency by integrating all the elements affecting nitrate-N at individual sub-basin level.

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