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Conservation Effects Assessment Project (CEAP)
CEAP-Wetlands Science Note

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Assessing Cumulative Impacts of Wetlands on Watershed Hydrology Using an Improved Hydrologic Modeling Approach

Summary of Findings

- Despite the importance of ecosystem services provided by wetlands in the Coastal Plain of the Chesapeake Bay Watershed, current understanding of wetland functions is mostly limited to individual sites. Overall catchment-scale wetland functions have rarely been investigated.
- This study coupled the Soil and Water Assessment Tool (SWAT) with two improved wetland modules for enhanced representation of riparian wetlands (RWs) and geographically isolated wetlands (GIWs) to better show the cumulative impacts of wetlands on hydrology in an agricultural watershed within the Coastal Plain of the Chesapeake Bay Watershed.
- Simulation results show that GIWs play a significant role in controlling hydrological processes in up-gradient areas and downstream flow. GIWs increase groundwater flow while decreasing surface runoff, subsequently leading to increased stability of stream flow. Simulated removal of GIWs has the opposite effect, increasing surface runoff by 9%, decreasing groundwater flow by 7%, and decreasing groundwater recharge by 14%.
- GIWs provide greater hydrological impact in controlling downstream flow than RWs, likely because GIWs have a much greater water storage volume than RWs.
- Increased emphasis on protecting GIWs is critical for enhanced hydrological resilience to extreme flow conditions in this region.

Background

Historically, over 60% of wetlands have been lost in the Chesapeake Bay Watershed (USFWS 2002). Degradation of the Chesapeake Bay Watershed ecosystem by increasing agricultural nutrient loads has drawn attention to the importance of wetland conservation and protection as a potential cost-effective management practice (Van Houtven *et al.* 2012). As a result, wetland restoration and enhancement are considered important conservation practices in the region.

Two types of wetlands—Riparian wetlands (RWs) and a type of depressional wetland called "Delmarva bays" (referred to as "geographically isolated wetlands" (GIW) in this Science Note)—are densely distributed on the Coastal Plain of the Chesapeake Bay Watershed, partly due to low topographic relief and high groundwater levels (Tiner 2003; Lang *et al.* 2012). Angier *et al.* (2002) showed that RWs are effective at removing agricultural pollutants at the field-scale. Similarly, studies have shown that GIWs efficiently reduce nutrients coming from agricultural land (Jordan *et al.* 2003; Denver *et al.* 2014). These previous studies demonstrate the potential role of RWs and GIWs in improving water quality at the field scale in this region. However, how wetlands affect aggregate water quantity at the landscape or catchment scale remains largely unknown.

In this study, we used the Soil and Water Assessment Tool (SWAT) model coupled with two improved wetland modules—the riparian wetland module (RWM) and the geographically isolated wetland module (GIWM)—to investigate the cumulative impacts of both RWs and GIWs on watershed hydrology for an agricultural watershed within the Coastal Plain of the Chesapeake Bay Watershed. The two modules were added to provide proper identification of and accounting for RWs and GIWs.

Using the improved modeling approach, we investigated two questions: 1) What is the hydrologic role of GIWs at the catchment scale? and 2) Which type of wetland (GIWs or RWs) has greater influence on downstream flow in the region?

Assessment Approach

Study Sites

The study site was the Tuckahoe Creek Watershed (approximately 220 km^2), a subwatershed characterized by low topographic relief in the upper region of the Choptank River Watershed, on the Coastal Plain of the Chesapeake Bay Watershed (Fig. 1). The Choptank River Watershed is designated an "impaired watershed" by the

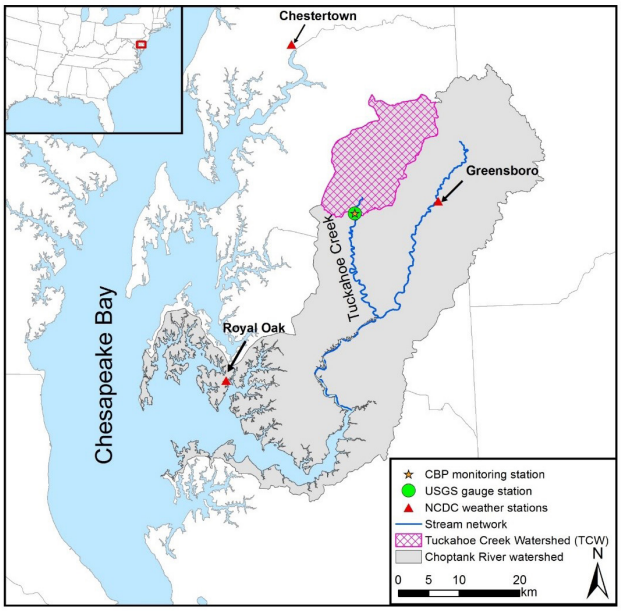


Figure 1. Location of the Tuckahoe Creek Watershed.

U.S. Environmental Protection Agency due to excessive sediment and nutrient loads (McCarty *et al.* 2008). Therefore, this watershed has been targeted as a Benchmark Watershed study site by the U.S. Department of Agriculture (USDA) Conservation Effects Assessment Project (CEAP). In the Tuckahoe Creek Watershed, agriculture is the primary land use type (54%), followed by forest (32.8%), pasture (8.4%), urban (4.2%), and water body (0.6%) (Lee *et al.* 2016).

Soil and Water Assessment Tool (SWAT)

The SWAT model is a semi-distributed, continuous time step, hydrologic model developed to examine the impacts of human activities and environmental stressors on hydrology, nutrient cycles, and pesticide loads within an agricultural watershed (Neitsch *et al.* 2011). SWAT subdivides a watershed into subwatersheds and further into hydrologic response units (HRUs) using geospatial data (e.g., Digital Elevation Model, land use, and soil maps). The model simulates water and nutrient cycles at the scale of individual HRUs, which are aggregated at the subwatershed and then watershed level via routing processes.

Improving Wetland Modules Within the SWAT Model

The SWAT default wetland modules account for individual wetlands and potholes. Our approach was designed to enhance the spatial representation of two additional types of wetlands (RWs and GIWs) and their hydrologic processes. To achieve this, we added two improved wetland modules (RWM and GIWM, Fig. 2) to the SWAT model. The GIWM, developed by Evenson *et al.* (2015), is a modified version of the SWAT default pothole module that better represents the hydrologic impacts of GIW contributing areas by defining spatially explicit individual GIWs and their contributing areas. The SWAT default pothole module assumes that inflow from GIW contributing areas to GIWs is only made via surface flow. Evenson *et al.* (2015) modified the SWAT source code (Rev 488) to route surface and subsurface flow (i.e., lateral and groundwater flow) generated within contributing HRUs to GIW HRUs, enabling the GIWM to simulate outflow from GIW contributing areas to be directed to GIWs. The RWM, developed by Liu *et al.* (2008), better represents "bi-directional" water exchange between an RW and the adjacent stream segment at the subwatershed scale within SWAT compared to the default SWAT wetland module that only represents one-directional flow from a RW to the adjacent stream segment.

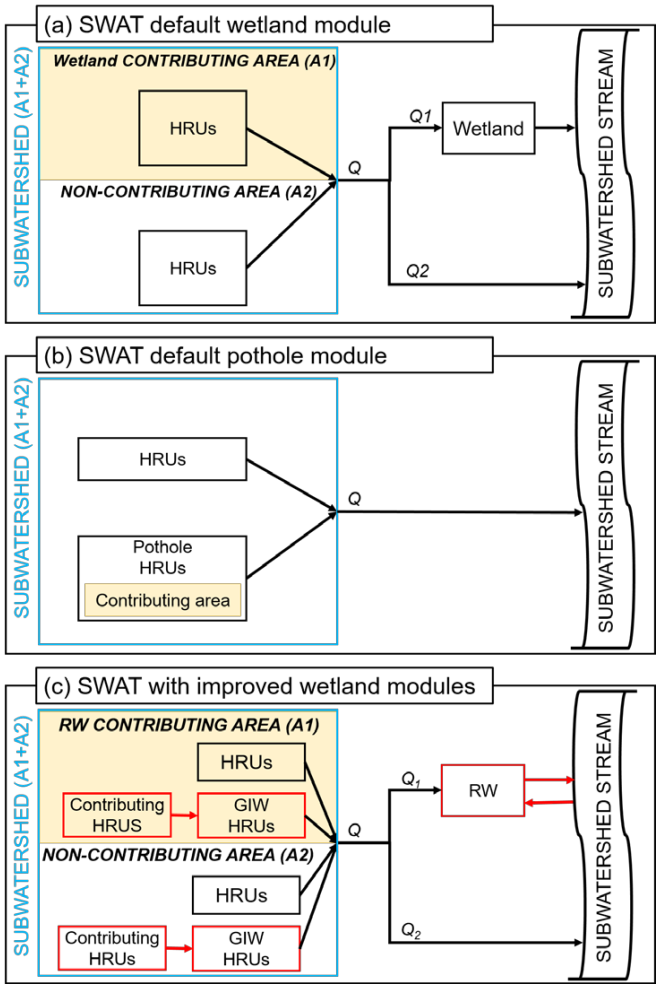


Figure 2. Flowcharts for SWAT default (a) wetland and (b) pothole modules and for (c) SWAT with improved wetland modules. Improved hydrologic processes by modules are highlighted in red. Q is the sum of water generated in the subwatershed. Q1 and Q2 are calculated by Q×(A1/(A1+A2)) and Q×(A2/(A1+A2)), respectively. The areal proportion of A1 or A2 to A1+A2 is considered for Q1 and Q2, but the spatial location of A1 and A2 is not regarded.

Model Calibration and Validation

The SWAT model coupled with the two wetland modules (RWM and GIWM) was calibrated and validated following a 2-year "warm-up" period (1999-2000) against daily streamflow collected by the U.S. Geological Survey gauge station #01491500 (Fig. 1). The warm-up period was followed by a 5-year calibration period (2001-2005) and then a 5-year validation period (2006-2010). We performed calibration after adjusting parameter values within an allowable range, following the SWAT model technical guidelines (Moriasi et al. 2007). We chose a set of parameters representing best model performance while satisfying the daily SWAT model performance criteria (Nash-Sutcliffe efficiency coefficient (NSE) > 0.2 and Percent-bias ≤ ±25) proposed by Records et al. (2014). Details about NSE and Percent-bias are available in Moriasi *et al.* (2007).

Wetland Loss Scenarios

We prepared multiple wetland loss scenarios considering historical wetland loss patterns (Tiner *et al.* 1994) and wetland configuration impacts on water quality (Denver *et al.* 2014). The baseline scenario (no wetland loss) was set as the existing wetland conditions derived from the National Wetlands Inventory geospatial dataset (Fig. 3). In scenario 1, we removed all GIWs as an extreme loss scenario, so only RWs remained. In scenario 2, we removed all GIWs directly abutting croplands, dividing GIWs adjacent to croplands into two groups based on their locations either downgradient or upgradient of croplands. If a GIW was closer to a stream line than its abutting cropland, we treated it as a downgradient GIW; otherwise we considered it an upgradient GIW (see inset map at bottom left of Fig. 3). In scenario 3, we removed all downgradient GIWs

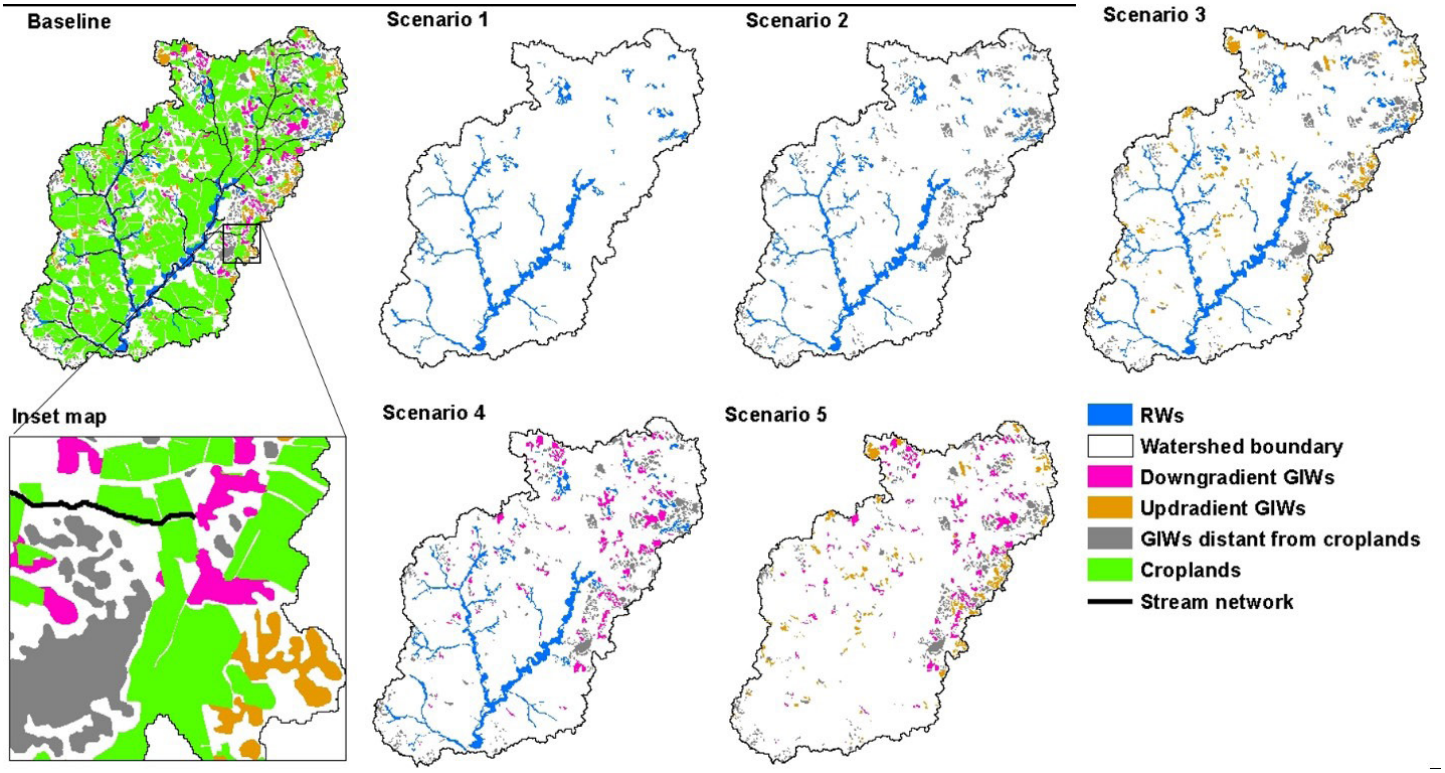


Figure 3. Spatial distribution of wetlands under the baseline (i.e., no wetland loss) and loss scenarios.

to show the effects of upgradient GIWs. In scenario 4, we removed all upgradient GIWs so only the effects of downgradient GIWs remained; these downgradient GIWs have the highest capacity to capture agricultural runoff. To compare the impacts of GIWs on downstream flow with RWs, we created scenario 5 in which we removed all of the RWs and only the GIWs remained. The five scenarios are summarized in Table 1.

Quantifying GIW Impacts

We assessed the cumulative impacts of GIWs and the linkage of upstream-downstream hydrological processes by analyzing hydrologic variables from upland areas to the watershed outlet over 10 years (2001 to 2010; McLaughlin *et al.* 2014). We first calculated annual average inflow to GIWs from their contributing areas and infiltration from GIWs into the underlying soil at the watershed scale. Then, we evaluated changes in watershed-scale water budget in upstream areas due to GIW losses using an annual average of hydrologic variables (surface runoff, groundwater flow, groundwater recharge, and evapotranspiration (ET)). Finally, we examined streamflow collected at the watershed outlet to evaluate downstream flow in response to GIW losses. We assessed the overall downstream flow pattern via the flow duration curve that represents a cumulative distribution of water discharge. We computed the baseflow contribution to streamflow to assess variability of downstream flow by GIW loss scenarios (Smakhtin and Batchelor 2005).

Assessment Findings

Model Performances

Simulated daily streamflow was in good agreement with observations. Daily model performance measures exceeded the acceptable performance criteria suggested by Records *et al.* (2014), both for the calibration and the validation periods (Fig. 4). The

Table 1. The wetland area (ha) and volume (10^4 m^3) for baseline and loss scenarios.

Scenario	Descriptions	GIW area total	Total GIW volume	RW area	RW volume	Contributing areas of total GIWs	Total loss area of GIW
1	GIWs removed, RWs remained	0	0	1,358	1,437	0	2,083
2	GIWs abutting croplands removed and labeled as either downgradient or upgradient of croplands	880	1,453	1,358	1,437	731	1,203
3	Shows effects of upgradient GIWs because all downgradient GIWs were removed	1,408	2,044	1,358	1,437	1,171	1,203
4	Shows effects of downgradient GIWs because all upgradient GIWs were removed	1,555	2,665	1,358	1,437	1,227	675
5	RWs removed, GIWs remained	2,083	3,257	0	0	1,668	528
Baseline	No loss (existing conditions)	2,083	3,257	1,358	1,437	1,668	0

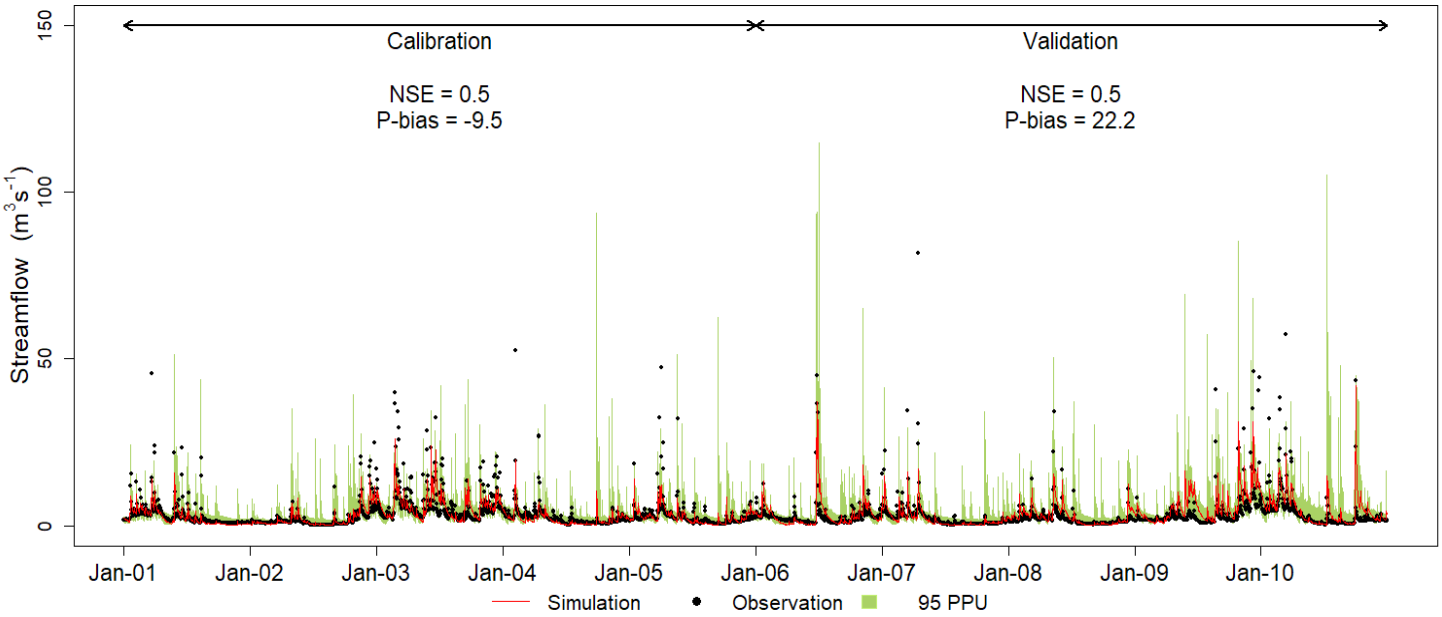


Figure 4. Comparison of daily simulated and observed streamflow during the 5-year calibration period (2001-2005) and the 5-year validation period (2006-2010).

NSE was 0.5 for both the calibration and the validation periods, and percent-bias was -9.5 and 22.2 for the calibration and the validation periods, respectively.

GIW Impacts on Contributing Areas

Under the baseline scenario (no wetland loss), 0.18 $m^3 \cdot s^{-1}$ was routed to GIWs from contributing areas of 1,670 ha via surface runoff, lateral flow, and groundwater, and 0.03 $m^3 \cdot s^{-1}$ infiltrated into the bottom of GIWs (Fig. 5). This inflow to GIWs, from both surface and subsurface water, mostly infiltrates into the soils because of their high hydraulic conductivity, and then this water is routed to nearby streams via groundwater flow. When the GIWs were removed (scenario 1), the inflow-contributing areas decreased from 1,670 ha (baseline) to 0 ha (Table 1), so no inflow reaches the GIWs and no infiltration occurs.

GIW Impacts on Watershed-Level Water Budget

Figure 6 shows the annual average of watershed-scale hydrologic variables under the baseline and GIW loss scenarios. Complete removal of GIWs (scenario 1) led to an increase in surface runoff of 9%, a decrease in groundwater flow of 7%, and a decrease in groundwater recharge of 14% (Fig. 6a,b,c). These findings are consistent with others that show that reduced water interception due to GIW removal leads to an increase in direct water transport from the land to nearby streams via surface runoff, while a decrease in water infiltration leads to a reduction in groundwater recharge and flow (Hayashi *et al.* 2003; Cohen *et al.* 2016).

In our studies, the increased surface runoff and decreased groundwater flow relative to baseline were proportional to the area of GIW loss as change level rose from scenario 4 (smallest loss) to scenario 1 (greatest loss) (Fig. 6a,b). Compared to the baseline, removal of all GIWs (scenario 1) led to a remarkable change in inflow to streams during the two extreme flow conditions by increasing inflow to streams during high-flow conditions (greater than flow percentiles at a 5% threshold) by 91% (2.1 $m^3 \cdot s^{-1}$) and by decreasing inflow to streams by 17% (0.17 $m^3 \cdot s^{-1}$) during low-flow conditions (lower than flow percentiles at a 95% threshold; Fig. 6e,f). Removal of GIWs caused immediate increases in surface runoff in response to precipitation events and a decrease in groundwater flow that helps maintain a stable flow pattern (Winter 2007).

GIW Impacts on Downstream Flow

The comparison of flow duration curves between the baseline and GIW loss scenarios (scenarios 1-4) demonstrated that GIW removal increased the variability of downstream flow by decreasing downstream flow during low-flow conditions and increasing it during high-flow conditions (Fig. 7a). This pattern was consistent with inflow to streams indicating contrasting patterns under low- and high-flow conditions (Fig. 6e,f). Therefore, changes in upstream water budget caused by GIW removal, such as increased contribution of upstream flows to downstream flow via surface runoff and lowered water holding capacity on upland areas, collectively resulted in increasing the variability of downstream flow.

We calculated the relative contributions of baseflow and quickflow to streamflow at a daily time step and averaged the relative contributions over the simulation period of 2001-2010 (Fig. 7b). The baseline baseflow contribution was 6% higher than in scenario 1, which coincided with changes in the watershed-scale hydrologic variables as GIW removal increased surface runoff contribution to streamflow while decreasing groundwater flow contribution.

Comparing GIWs and RWs

Our simulation results showed that removal of all GIWs (scenario 1)

induced greater changes in downstream flow compared to removal of all RWs (scenario 5) at the study site. The variability of downstream flow during low- and high-flow conditions considerably increased following GIW removal compared to variability after RW removal (Fig. 6e,f). In addition, the relative contribution of baseflow to streamflow was 5% higher with RW removal than with GIW removal (Fig. 7b).

Overall, the results indicate GIWs provide greater hydrological impact in controlling downstream flow than RWs at our study site. This was likely due to the much greater water storage volume of GIWs ($3{,}260\times10^4$ m^3) compared to RWs ($1{,}440\times10^4$ m^3). GIWs trap water generated on upland areas, while RWs trap water moving from uplands to streams. Thus, wetlands with greater storage volume exert greater impacts on water loadings coming from upland areas, leading to less fluctuation of downstream flow.

Implications

Simulated GIW impacts on upstream water transport mechanisms have implications for wetland water quality benefits, especially for particulate pollutants transported by surface runoff. Organic N and P move via surface runoff as those nutrients are attached to sediment particles, while transport of dissolved nutrients occurs mostly through leaching. Previous studies have shown that pollutants are reduced by GIWs (Jordan *et al.* 2003; Denver *et al.* 2014). Accordingly, GIW removal could increase pollutant loadings to nearby streams.

Our findings help to infer GIW water quality benefits from simulated hydrologic changes caused by GIW removal because, in addition to GIW water quantity functions, our study indirectly demonstrates GIW impacts on mitigating water quality degradation. Our simulation results show that removal of GIWs led to increasing direct water flow from uplands to streams, especially under high-flow conditions.

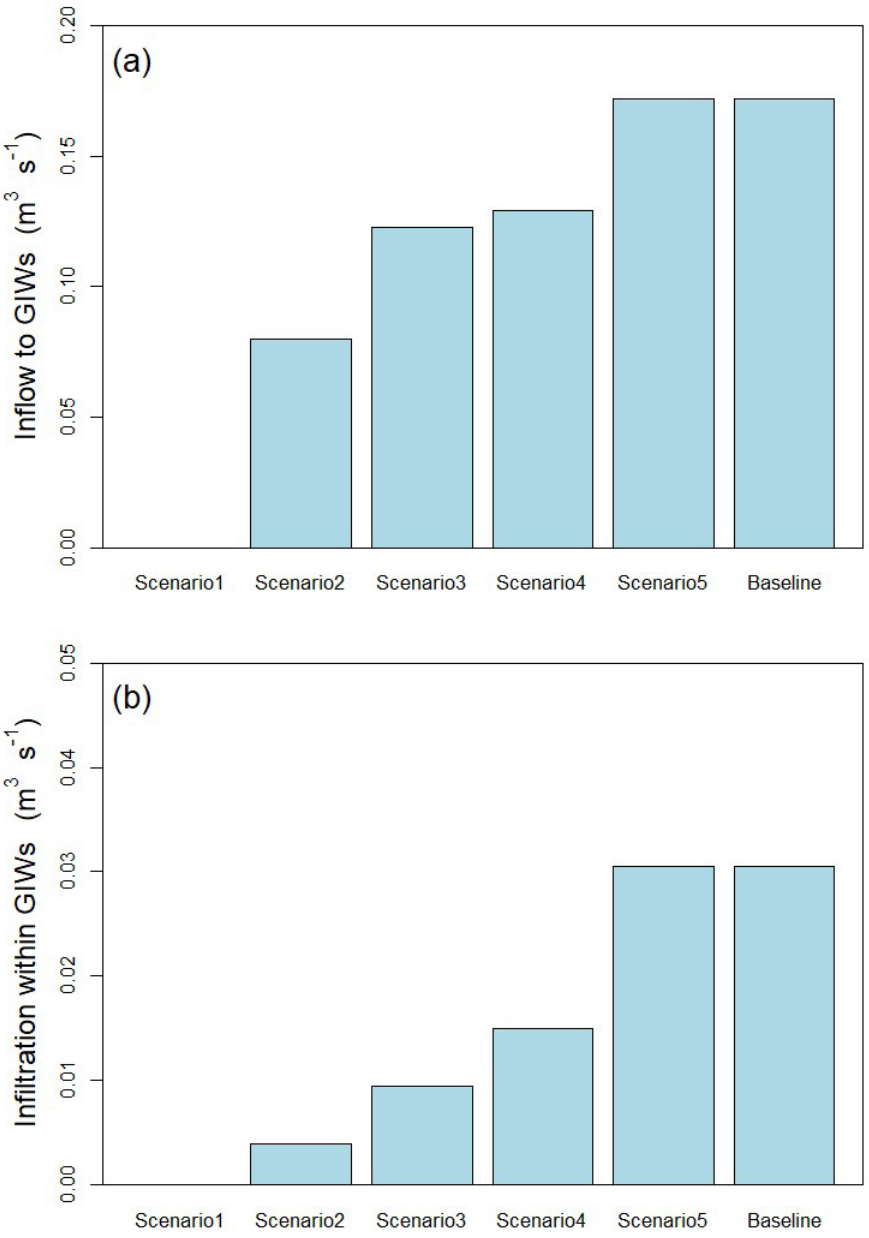


Figure 5. (a) Inflow to GIWs and (b) infiltration through the bottom of GIWs under the baseline (i.e., no wetland loss) and loss scenarios.

Conclusions

This study used an approach that coupled the SWAT model with two improved wetland modules to evaluate the cumulative impacts of GIWs on watershed hydrology within the Coastal Plain of the Chesapeake Bay Watershed. To demonstrate the hydrological impacts of GIWs, we developed several loss scenarios by removing all or portions of baseline GIWs indicated in the National Wetlands Inventory geospatial dataset. Our simulation results indicate that GIWs serve as important landscape features to help control watershed hydrology in the Tuckahoe Creek Watershed. In simulated loss scenarios, the removal of GIWs led to increased surface runoff and decreased groundwater flow contributions to water transport from uplands to nearby streams. As a result, the variability of downstream flow was substantially increased following the removal of GIWs, especially during extreme flow conditions. In addition, the removal of GIWs resulted in an increase in the inter-monthly variability of downstream flow and decreased baseflow contributions to streamflow. Compared to the removal of RWs, the removal of GIWs appeared to induce greater

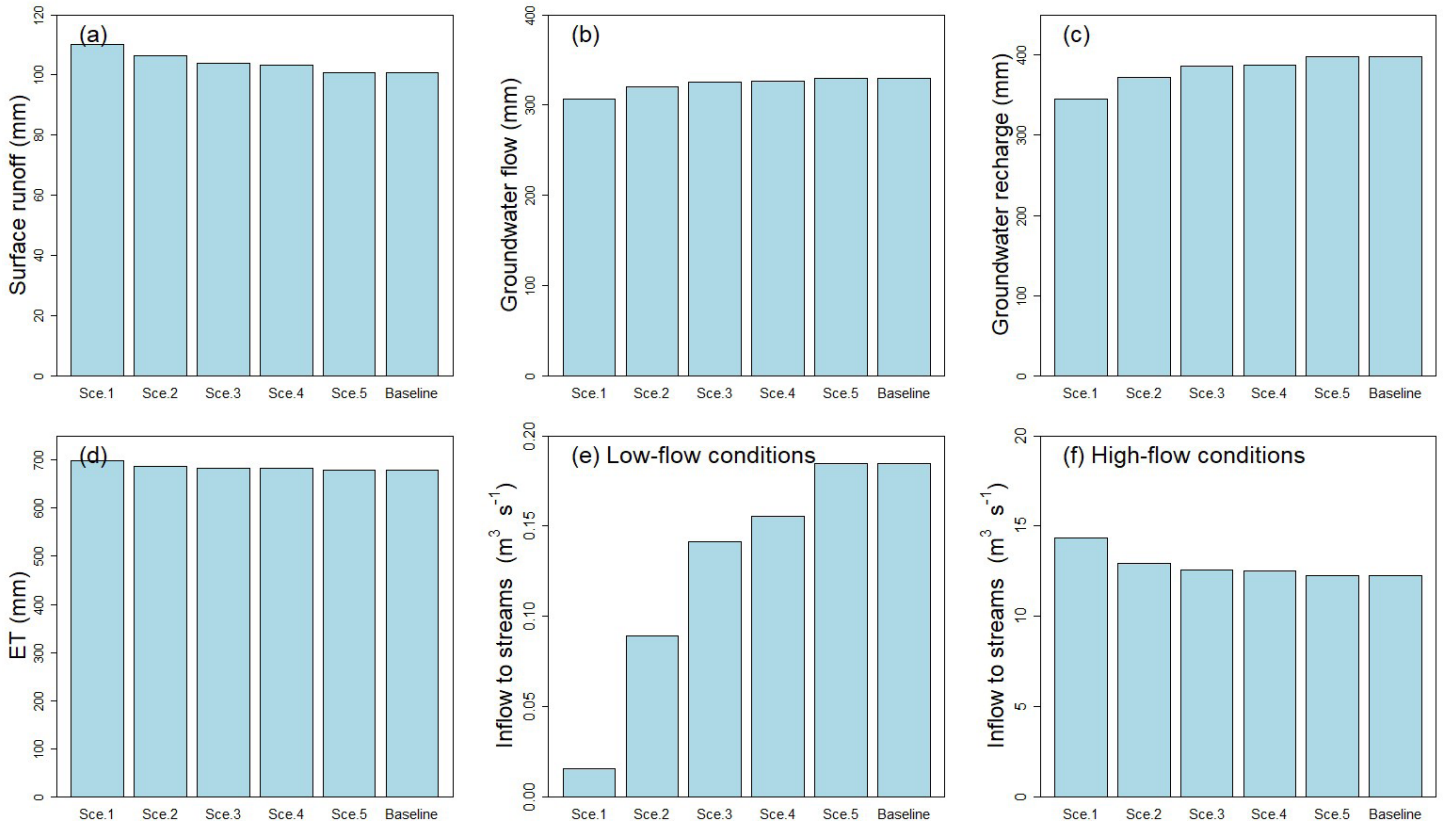


Figure 6. Annual average (a) surface runoff, (b) groundwater flow, (c) groundwater recharge, (d) evapotranspiration (ET), and inflow to streams at (e) low-flow and (f) high-flow conditions under the baseline (i.e., no wetland loss) and loss scenarios (sce).

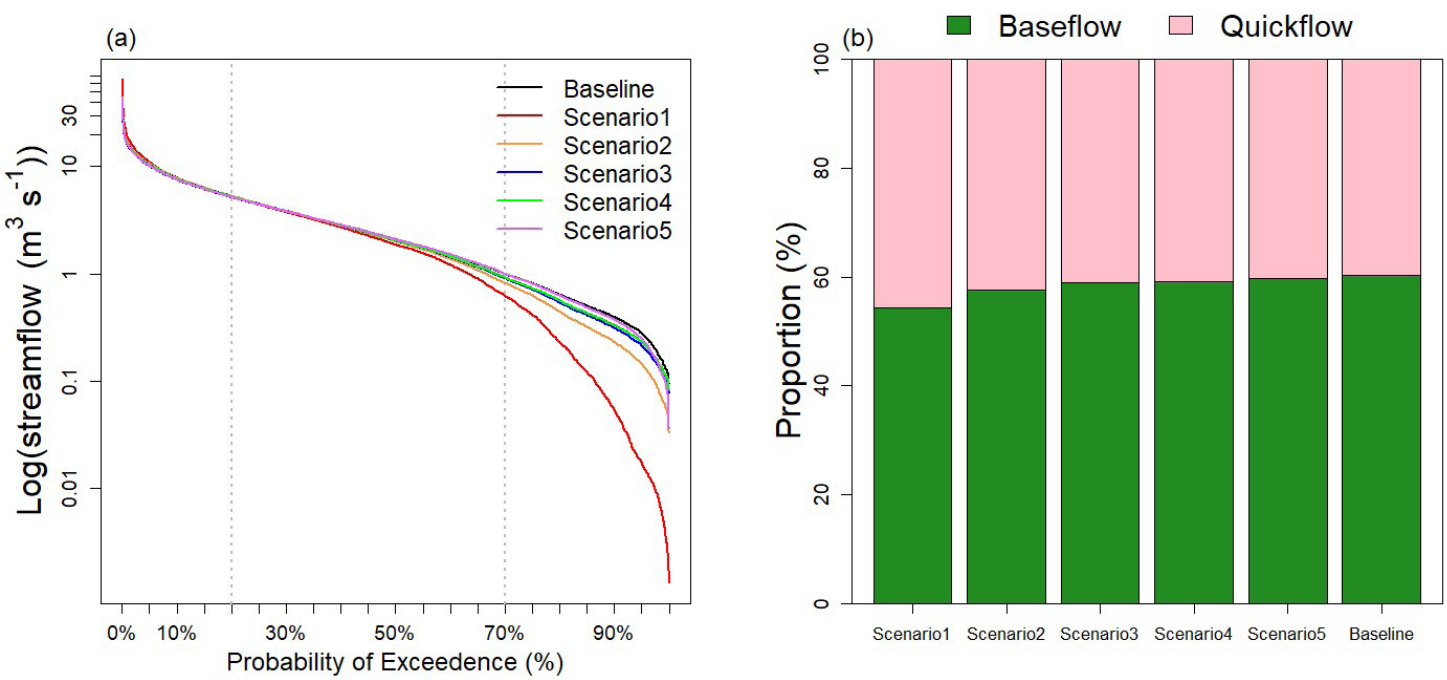


Figure 7. (a) Flow duration curves for the baseline and wetland loss scenarios (estimated using daily simulated streamflow at the watershed outlet) and (b) the proportions of baseflow and quickflow to streamflow under the baseline and wetland loss scenarios.

downstream flow fluctuations due to the greater water storage volume lost if GIWs were removed.

Based on these findings, we conclude that GIWs exert significant impacts on maintenance of upstream water budget and downstream flows in this region. Thus, GIW conservation can promote the hydrological resilience of downstream flow to extreme flow conditions. Mitigation of extreme flow conditions supports societal resilience to natural hazards, including flooding and drought, and helps maintain critical habitat for aquatic species. In addition, the findings emphasize the importance and necessity of ongoing wetland conservation projects for this region led by NRCS.

Conservation Effects Assessment Project: Translating Science into Practice

The Conservation Effects Assessment Project (CEAP) is a multiagency effort to build the science base for conservation. Project findings will help to guide USDA conservation policy and program development and help farmers and ranchers make informed conservation choices.

One of CEAP's objectives is to quantify the environmental benefits of conservation practices for reporting at the national and regional levels. Because wetlands are affected by conservation actions taken on a variety of landscapes, the Wetlands National Component complements the national assessments for cropland, wildlife, and grazing lands. The wetlands national assessment works through numerous partnerships to support relevant assessments and focuses on regional scientific priorities.

This project was conducted through collaboration among researchers at University of Maryland College Park; the University of Newcastle, Australia; and USDA-ARS Beltsville. Primary investigators on this project were S. Lee, I.-Y. Yeo, M.W. Lang, A.M. Sadeghi, G.W. McCarty, G.E. Moglen, and G.R. Evenson. This Science Note was compiled by Drs. S. Lee, G. McCarty, and Xia Li. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by USDA.

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