Title of the grant: Mapping and Monitoring of Wetland Dynamics for Improved Resilience and Delivery of Ecosystem Services in the Mid-Atlantic Region.
Type of report: Final Report
Name of the principal investigator: In-Young Yeo
Period covered by the report: April 1, 2012-March 31, 2018 (with no cost extension)
Name and address of the recipient's institution: Department of Geographical Sciences, University of Maryland, College Park
Grant number: NNX12AG21G

(1) *A comparison of actual accomplishments with the goals and objectives established for the period, the findings of the investigator, or both. Whenever appropriate and the output of programs or projects can be readily quantified, such quantitative data should be related to cost data for computation of unit costs.*

The overall objectives of this study are to (1) develop improved wetland mapping and change detection using remote-sensing data from multiple, complementary sensors at various temporal and spatial scales; (2) study the socioeconomic and physical drivers of wetland change affecting wetland extent and function at regional scales; (3) assess the impacts of multiple environmental stressors, particularly the anthropogenic ones; and (4) quantify the vulnerability of wetlands and wetland ecosystem services under multiple climate and land use change scenarios.

Over the entire project year, we were able to successfully achieve the project objectives and goals. We publish several papers from high impact journals, produced two Ph.D.s and one MS, and mentored two Post-doc researchers and two undergraduate student interns. Details are presented in Section (5).

We highlights the study findings most relevant to the project objectives and aims from selected papers in the following sub-sections.

a. <u>Obj. 1: Mapping wetlands and change dynamics:</u>

(a.1.) **Topographic Metrics for Improved Mapping of Forested Wetlands**
We investigated the predictive strength of forested wetland maps produced using digital elevation models (DEMs) derived from Light Detection and Ranging(LiDAR) data and multiple topographic metrics, including multiple topographic wetness indices (TWIs), a TWI enhanced to incorporate information on water outlets, normalized relief, and hybrid TWI/relief in the Coastal Plain of Maryland. LiDAR DEM based wetland maps were compared to maps of inundation and existing wetland maps. TWIs based on the most distributed FD8 (8 cells) and somewhat distributed D∞ (1–2 cells) flow routing algorithms were better correlated with inundation than a TWI based on a non-distributed D8 (1 cell) flow routing algorithm, but D∞ TWI class boundaries appeared artificial. The enhanced FD8 TWI provided good prediction of wetland location but could not predict periodicity of inundation. Normalized relief provided good prediction of inundation periodicity but was less able to map wetland boundaries. A hybrid of these metrics provided good measurement of wetland location and inundation periodicity. Wetland maps based on topographic metrics included areas of flooded forest that were similar to an aerial photography based wetland map. These results indicate that LiDAR based topographic metrics have potential to improve accuracy and automation of wetland mapping.

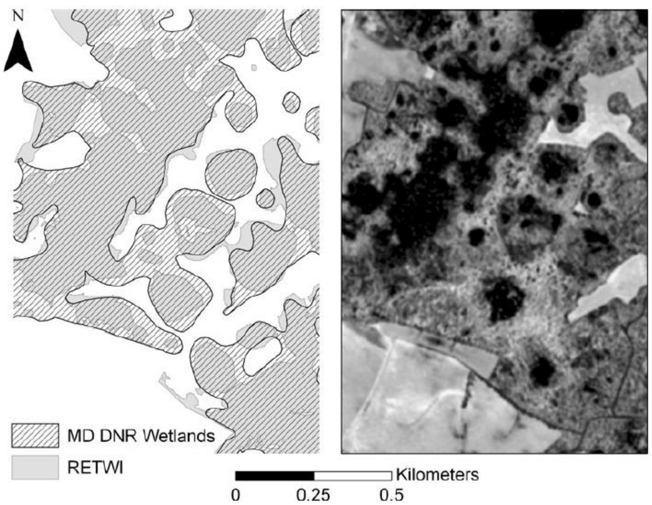


Fig. 1 Map showing the spatial relationship between MD DNR and Relief Enhanced TWI wetland maps for one location within the study area (left) and an average spring LiDAR intensity image for the same area (right)

(a.2.) Wetland inundation mapping and change monitoring using Landsat and airborne LiDAR data

This paper presents a new approach for mapping wetland inundation change using Landsat and LiDAR intensity data. In this approach, LiDAR data were used to derive highly accurate reference subpixel inundation percentage (SIP) maps at the 30-m resolution. The reference SIP maps were then used to establish statistical relationships between SIP and Landsat data. Inundation changes were mapped by applying the derived relationships to Landsat images acquired in different years. This approach was applied to the upper Choptank River sub-watershed to map wetland inundation for average (2005 and 2007), dry (2009), and wet (2010) years. The derived SIP maps revealed large changes in wetland inundation among dry, average, and wet years. Total areas of near complete inundation (SIP > 75%) and high inundation (SIP between 50% and 75%) in the wet year of 2010 were about five and three times of those in the dry year of 2009, respectively. The wet year also had more medium inundated areas (SIP between 25% and 50%) than the average and dry years, but low inundated areas (SIP < 25%) did not have any particular trend. The mapped inundation changes were found correlated with local drought conditions and stream flow, with the near complete inundated and highly inundated areas having the highest correlations. Given the fact that Landsat are globally available and LiDAR data are becoming increasingly more affordable and available, the approach developed in this study has potential for deriving historical inundation changes over the past decades and for monitoring ongoing changes over much larger areas than demonstrated in this study.

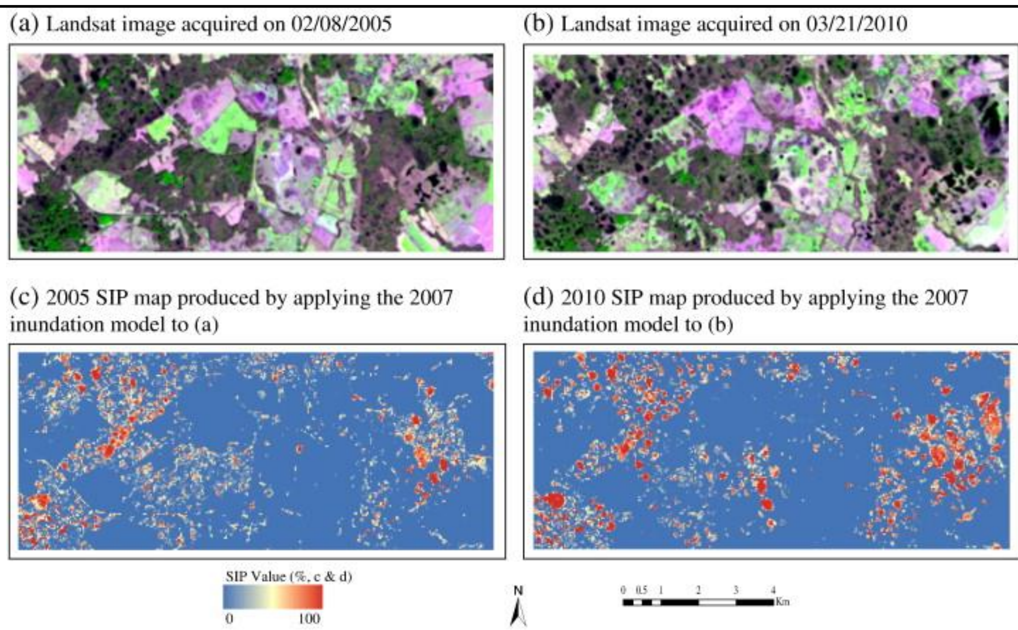


Fig. 2. 2005 (c) and 2010 (d) SIP maps predicted by applying the inundation model derived using 2007 data to the Landsat images acquired in 2005 (a) and 2010 (b), respectively.

The two Landsat images are shown with bands 5, 4, and 3 in red, green, and blue. Open water bodies and pixels with high SIP values should look dark in these images. Visually the inundation patterns in the two SIP maps matched those seen in the input Landsat images.

(a.3.) Monitoring of wetland inundation dynamics in the Delmarva Peninsula using Landsat time-series imagery from 1985 to 2011

Wetlands provide important ecosystem services, the provision of which is largely controlled by fluctuations in inundation and soil saturation. Inundation is highly dynamic and can vary substantially through time in response to multiple drivers, including precipitation and evapotranspiration. This research focused on developing a practical and effective framework for regional, long-term monitoring of wetland inundation dynamics using airborne LiDAR intensity data (Lang et al., 2013) and Landsat time-series imagery. Subpixel water fraction (SWF) maps indicating the percent of surface water within each 30-m pixel were generated on an annual basis over the entire Delmarva Peninsula on the East Coast of the United States from 1985 to 2011. Comprehensive accuracy assessments of the SWF maps were conducted using historical high-resolution aerial photography to determine the reference condition. The assessment resulted in an estimated root mean square error (RMSE) of 7.78% for the sample of open water areas (mean SWF was ~ 40% for this region of the map). Moreover, a separate accuracy assessment targeting inundation in wetlands (i.e. presence or absence of water) yielded an overall accuracy of 93%. Accuracies derived indicated that Landsat data can be calibrated to accurately extract long-term water information at the regional scale. Characteristics of inundation were examined with respect to different wetland types defined by water regime and dominant vegetation types, as well as different physical drivers. Results showed that tidal wetlands typically exhibited more intensive inundation than nontidal wetlands, and a higher degree of inundation was associated with emergent wetlands compared to wetland areas dominated by woody vegetation. Analysis of change drivers revealed that tide exerted a statistically significant influence on coastal inundation with r2 values of 32–36% and $p < 0.01$, whereas inundation changes in inland wetland areas were in part driven by precipitation with r2 values of 25–34% and $p < 0.08$. Because an up-to-date archive of Landsat imagery is globally available and LiDAR data are becoming increasingly more affordable, the developed framework can be easily implemented to generate a continuous inundation record in many regions of the globe to assist in ongoing and future studies focused on wetland hydrology and wetland management.

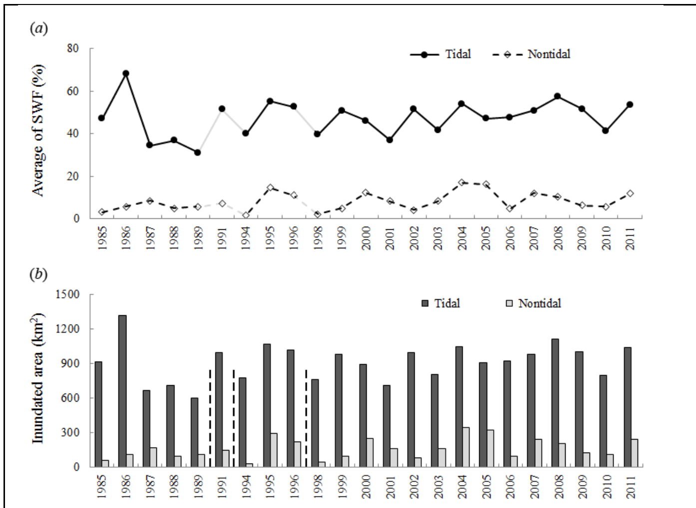


Fig 3: (a) Average of SWF and (b) inundated area for tidal and nontidal wetlands. Lines displayed in light gray in (a) and vertical dashed lines in (b) indicate gaps of the years that were not included in the analysis.

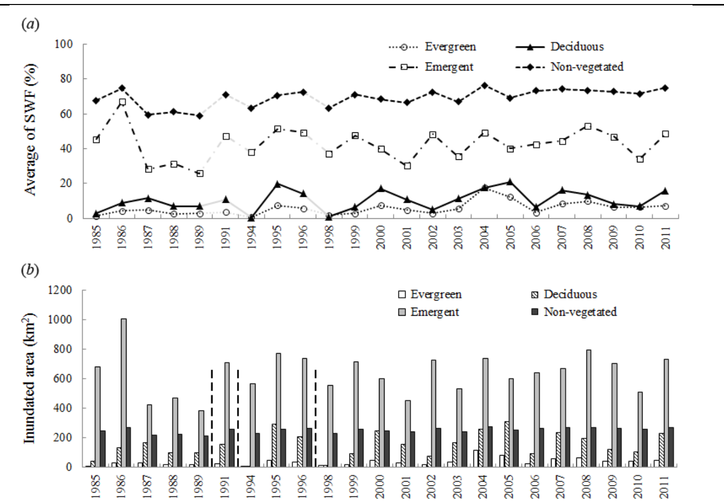


Fig 4: (a) Average of SWF and (b) inundated area for evergreen, deciduous, emergent, and non-vegetated wetlands. Lines delayed in light gray in (a) and vertical dashed lines in (b) indicate gaps of the years

b. Obj 2&3 Drivers of wetland changes:

(b.1.) A Spatio-temporal analysis of wetland loss and section 404 permitting on the Delmarva Peninsula from 1980 to 2010.

Geospatial approaches for wetland change analyses have emphasized the evaluation of landscape change on a local level, but have often neglected to examine and integrate regional trends and patterns of land use and land cover change as well as the impacts of wetland management policies. This study attempts to bridge the gaps by integrating a geospatial assessment of land cover change and a geostatistical analysis of the physical and anthropogenic drivers of wetland change to demonstrate how urban development, conservation, and climate change policy decisions influenced wetland change trends and patterns on the Delmarva Peninsula from 1980 to 2010. Historical data on the nine counties on the Delmarva Peninsula illustrate the dynamism of population growth, sprawl, and different wetland management strategies. Data sets from the National Oceanic and Atmospheric Administration, the Chesapeake Bay Program, and the U.S. Army Corps of Engineers, and the U.S. Census Bureau were assembled and gathered. A land cover database was developed and analyzed using geospatial techniques, such as cross tabulation matrices and hot spot density analyses, in order to quantify and locate land cover change between 1984 and 2010. The results highlighted that anthropogenic drivers such as urbanization and agriculture increased the loss of wetlands in coastal areas as well as suburban, forested, upland areas. The greatest quantity and percentage of loss occurred between 1992 and 2001, and was the result of increases in tourism and suburban sprawl (*e.g.*, the Housing Boom and roadway expansion). The majority of wetland loss tapered off after the real estate market crash in 2000, except on coastal areas suffering from sea level rise and shoreline erosion. The results also reinforced the need to address the negative impacts that agriculture and silviculture, which are exempt from Section 404 of the Clean Water Act, have on wetlands. Physical drivers and processes like inundation from sea level rise and soil erosion from surface runoff force communities to simultaneously adapt to coastal, suburban development and climate change. My results supported the hypothesis that an increase in development and wetland permitting signifies a risk of wetland loss. In the end, the study demonstrates that geostatistical modelling techniques can be used to predict wetland loss, and that model performance and accuracy can be improved by reducing the multicollinearity of independent variables. Planners and policymakers can use these models to better understand the wetland locations that are at greatest risk to loss, as well as the drivers and landscape conditions that have the greatest influence on the probability of wetland loss.

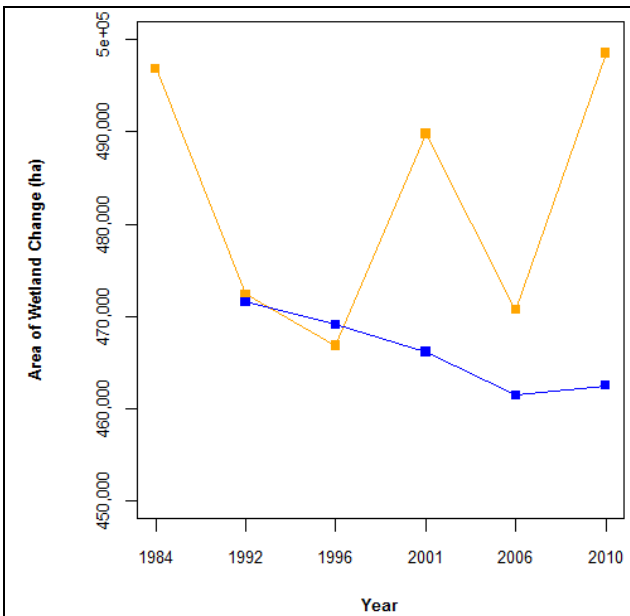


Fig.5 Temporal trends of the quantities of wetland change in the study area using the C-CAP, CBLCD, state LCDs, and archived NWI from 1984 to 2012.

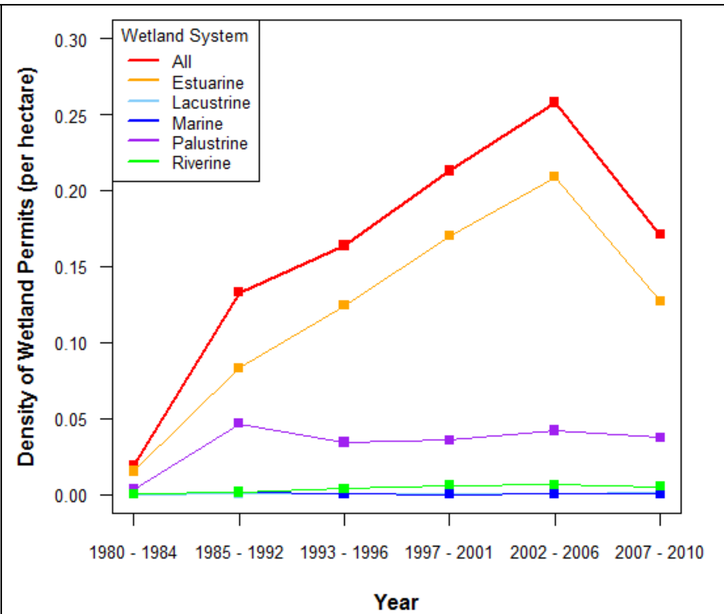


Fig 6: Time Series of the density of wetland permits by wetland system from 1980 to 2010.

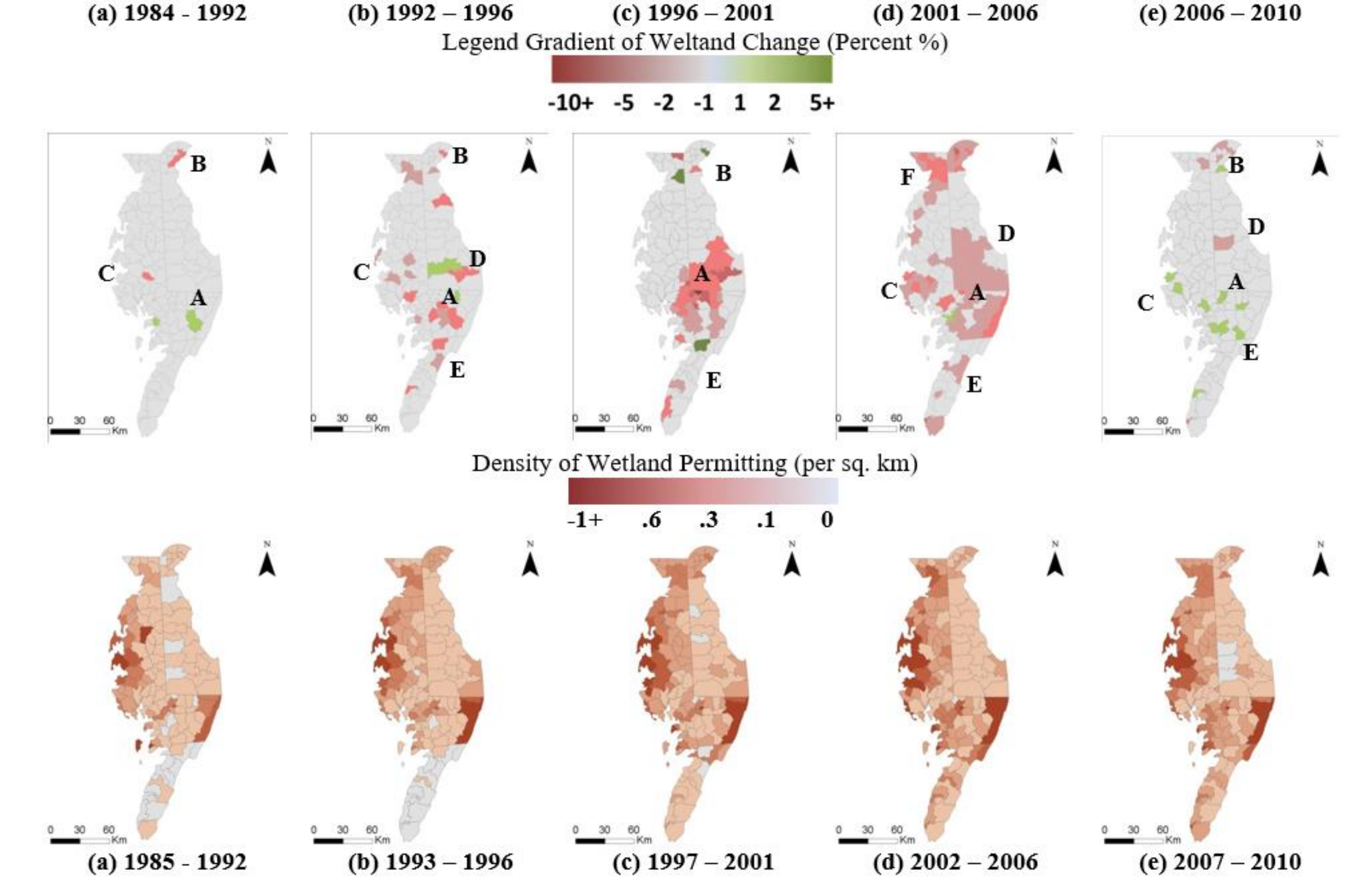


Fig 7: Maps illustrating 1) wetland loss by percentage at the minor civil division scale from 1984 to 2010 (A –E): (A) CBLCD from 1984 to 1992 and (B-E) C-CAP from 1992 to 2010, and 2) the density of wetland permitting (per ha) at the minor civil division scale from 1984 to 2010.

c. <u>Obj. 4: Ecosystem Assessment and Wetland Vulnerability:</u>

(c.1.) Improving the catchment scale wetland modeling using remotely sensed data

This study presents an integrated wetland-watershed modeling approach that capitalizes on inundation maps and geospatial data to improve spatial prediction of wetland inundation and assess its prediction uncertainty. We outline problems commonly arising from data preparation and parameterization used to simulate wetlands within a (semi-) distributed watershed model. We demonstrate how wetland inundation can be better captured by the wetland parameters developed from remotely sensed data. We then emphasize assessing model prediction using inundation maps derived from remotely sensed data. This integrated modeling approach is tested using the Soil and Water Assessment Tool (SWAT) with an improved riparian wetlands (RWs) extension, for an agricultural watershed in the Mid-Atlantic Coastal Plain, US. This study illustrates how spatially distributed information is necessary to predict inundation of wetlands and hydrologic function at the local landscape scale, where monitoring and conservation decision making take place.

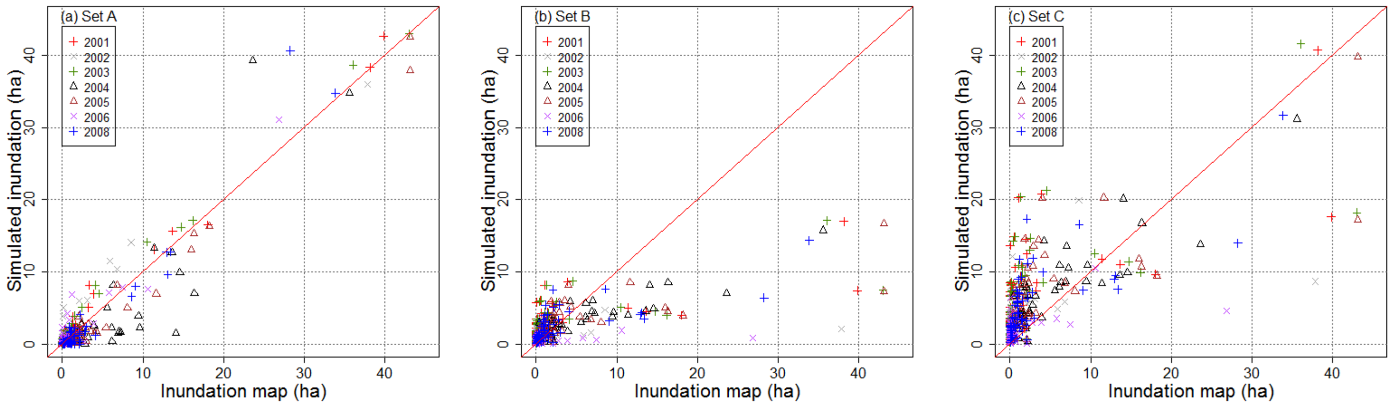


Fig 8: The relationship between inundation maps and simulated inundation areas within riparian wetlands from (a) Set A, (b) Set B, and (c) Set C, assessed at the sub-watershed scale under different weather conditions (×: Dry, +: Normal, and Δ: Wet condition) [Set A developed from inundation maps while Set B & C based on the existing literature and commonly applied methods].

(c.2.) Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules

Despite recognizing the importance of wetlands in the Coastal Plain of the Chesapeake Bay Watershed (CBW) in terms of ecosystem services, our understanding of wetland functions has mostly been limited to individual wetlands and overall catchment-scale wetland functions have rarely been investigated. This study is aimed at assessing the cumulative impacts of wetlands on watershed hydrology for an agricultural watershed within the Coastal Plain of the CBW using the Soil and Water Assessment Tool (SWAT). We employed two improved wetland modules for enhanced representation of physical processes and spatial distribution of riparian wetlands (RWs) and geographically isolated wetlands (GIWs). This study focused on GIWs as their hydrological impacts on watershed hydrology are poorly understood and GIWs are relatively vulnerable to loss. Multiple wetland scenarios were prepared by removing all or portions of the baseline GIW condition indicated by the U.S. Fish and Wildlife Service National Wetlands Inventory geospatial dataset. We further compared the impacts of GIWs and RWs on downstream flow (i.e., streamflow at the watershed outlet). Our simulation results showed that GIWs strongly influenced downstream flow by altering water transport mechanisms in upstream areas. Loss of all GIWs reduced both water routed to GIWs and water infiltrated into the soil through the bottom of GIWs, leading to an increase in surface runoff of 9% and a decrease in groundwater flow of 7% in upstream areas. These changes resulted in increased variability of downstream flow in response to extreme flow conditions. GIW loss also induced an increase in month to month variability of downstream flow and a decrease in the baseflow contribution to streamflow. Loss of all GIWs was shown to cause a greater fluctuation of downstream flow than loss of all RWs for this study site, due to a greater total water storage capacity of GIWs. Our findings indicate that GIWs play a significant role in controlling hydrological processes in upstream areas and downstream flow and, therefore, protecting GIWs is important for enhanced hydrological resilience to extreme flow conditions in this region.

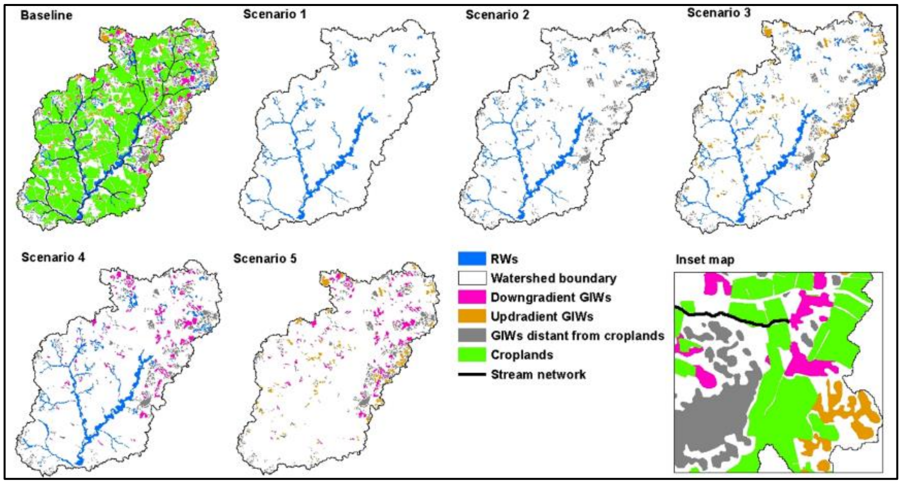


Fig.9**.** The spatial distribution of wetlands under the baseline (i.e., no wetland loss) and loss scenarios.

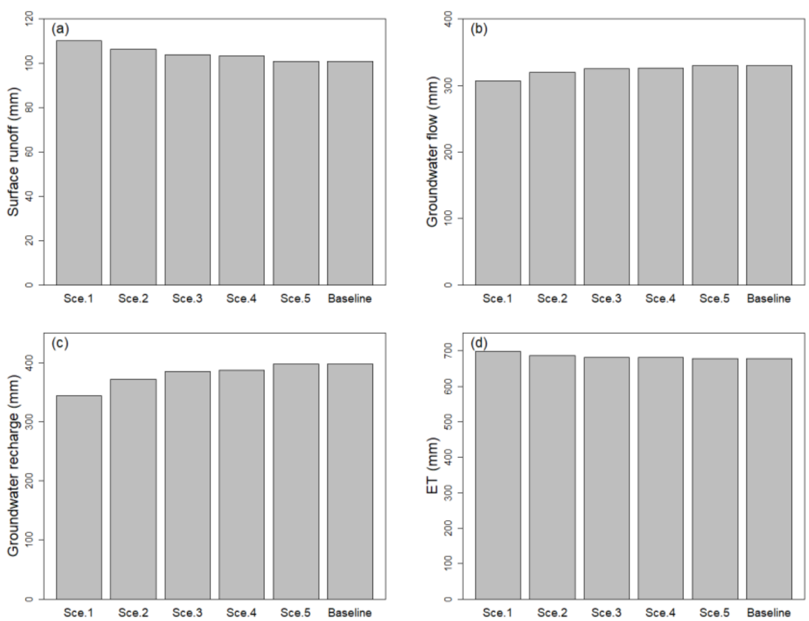
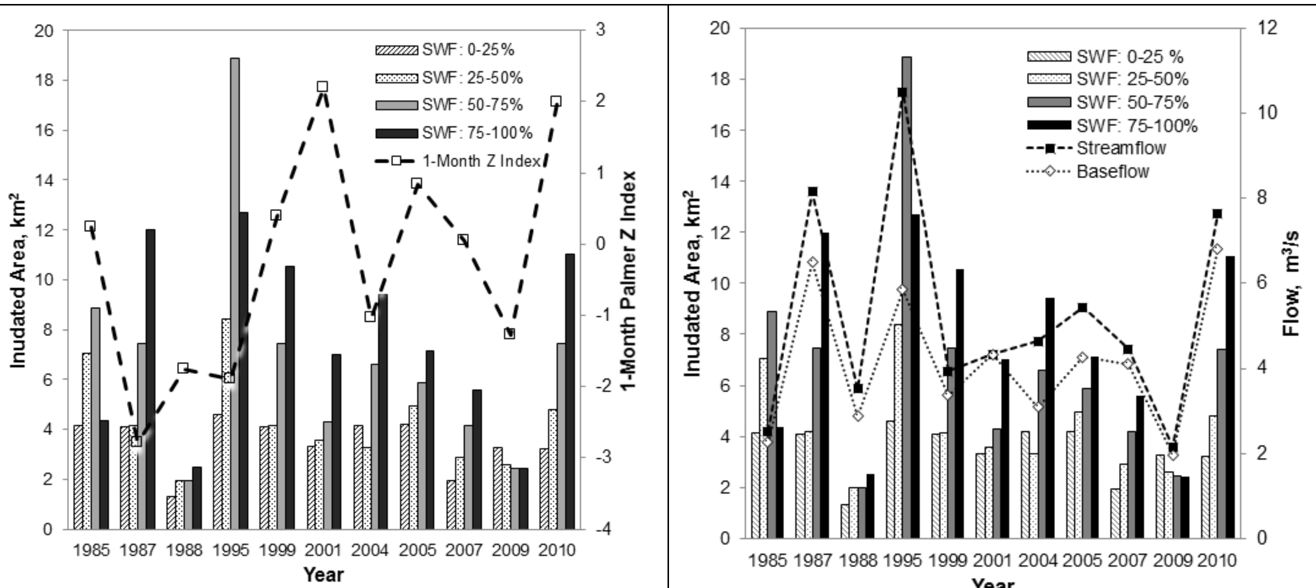


Fig. 10. Annual average of the watershed-scale hydrologic variables under the baseline and GIW loss scenarios: (a) surface runoff, (b) groundwater flow, (c) groundwater recharge, and (d) ET. Note: Sce. indicates Scenario.

(c.3.) Mapping the landscape-level hydrological connectivity of headwater wetlands to downstream waters: a geospatial modeling approach - Part I.

Headwater wetlands affect ecosystem integrity of downstream waters; however, many wetlands – particularly geographically isolated wetlands (GIWs) – continue to be at risk. Current regulations in the United States (US) require a clear demonstration of the surface water connectivity of wetlands to and their cumulative impacts on downstream waters for their protection. Moreover, while future US federal regulations for wetlands are in flux, wetland-stream connections and their cumulative influence on downstream waters will likely continue to be crucial to the future jurisdictional status of wetlands. We present a novel multi-phase geospatial modelling method to help elucidate the hydrological relationship between GIWs and downstream waters at the landscape scale. The approach used inundation maps derived from time series remotely sensed data, weather and hydrological records, and ancillary geospatial data including information from the US Fish and Wildlife Service National Wetlands Inventory (NWI) between 1985 and 2015. The study site was a headwater catchment (292 km^2) of the Choptank River Basin, located in the Mid-Atlantic region of USA, which contained a large number of Delmarva bays. The results from the geospatial analysis showed inundation extent within GIWs varied, in aggregate, in response to weather variability (r = 0.58; *p-value* =0.05), and was well correlated with streamflow (r = 0.81; *p-value* < 0.01) and base flow (r = 0.57; *p-value* < 0.1) conditions. The relationship between inundation patterns and stream discharge also varied with National Wetlands Inventory (NWI) geospatial dataset hydrologic modifiers. The GIWs with longer hydroperiods exhibited stronger correlations with stream discharge. However, inundation in saturated wetlands (which are inundated seldom or only for a very short period) were less correlated with stream discharge. This analysis suggests the mutual reliance (i.e., connection) of wetlands and streams on groundwater. GIWs appeared to function in aggregate, and it is likely that the combined effect of these wetlands significantly influenced downstream waters.



(a) Inundated Area vs. Short-term Weather Condition

(b) Inundated Area vs. Stream discharge at the watershed outlet

Fig 11. Changes in Inundation Extent, Weather Variability, and Streamflow between 1985 and 2010

Note: Fig 11 a&b show the ranges of SWF (% inundation at 30-m) within wetlands in the study area under different weather and hydrologic conditions. High inundation (SWF>50%) show strong correlation to stream discharge. Fig 11.a shows inconsistency in aggregated inundation in 1987 and 1995 with weather conditions (shown with 1-month Z index), and Fig 11.b inconsistency between the weather conditions and stream flows. The local storms effects were not shown from the drought index (1-Month Palmer Z score), but were evident from daily streamflow and SWF maps. Inundated areas of both geographically isolated (GIW) (slope =1.61, r^2=0.46) and surface water connected (SWC) (slope =0.27, r^2=0.47) wetlands show a statistically significant relationship (*p-value*<0.05) with 1-Month Palmer Z Index.

(c.4.) Mapping landscape-scale hydrological connectivity of headwater wetlands to downstream water: a catchment modelling approach - Part 2.

In section (c.3), we presented a rapid assessment method for mapping inundation of seasonal forested wetlands and quantifying their cumulative landscape-scale hydrological connectivity with downstream water using time series remote sensing products and statistical methods. This study suggested strong hydrological coupling between geographically isolated wetlands (GIWs) and downstream water at the seasonal timescale via groundwater. As a follow-up, this paper investigates the hydrological connectivity of GIWs with downstream water and cumulative catchment-scale hydrological impacts over multiple time scales. Specific modifications improving representation of wetland processes were incorporated into the

Soil and Water Assessment Tool (SWAT), a semi-distributed physically-based continuous watershed simulation model. A version of SWAT with improved wetland function (SWAT-WET) was applied to the Greensboro Watershed located in the Mid-Atlantic Region of USA (as in [c.3]) and simulated hydrological processes at a daily time scale over 1985-2015 under the two contrasting land use scenarios (i.e., with the presence and absence of GIWs). The comparative analysis of simulation outputs elucidated how GIWs could influence the partitioning of precipitation between evapotranspiration and terrestrial water storage (i.e., vertical fluxes), recharge soils and groundwater, and affect water transport mechanism and routing processes that generate stream flow. The model results showed GIWs influenced catchment water budget and stream flow generation processes over the long-term (30 year), inter-annual, and monthly time scales. Through the hydrological continuum that GIWs created between surface water and groundwater, the study watershed increased terrestrial water storage during the wet season, which in turn supported wetlands and buffered the dynamics of shallow ground water during dry season. The inter-annual modeling analysis illustrated that densely distributed GIWs can exert strong hydrological influence on downstream water by regulating surface water runoff, while maintaining groundwater recharge and AET under changing (wetter) climate conditions. The study findings highlight the hydrological connectivity of GIWs with downstream waters and the cumulative hydrological influence of GIWs as hydrologic sources to downstream ecosystem through different runoff processes over multiple time spans, providing important scientific insights and support for future management and protection of GIWs.

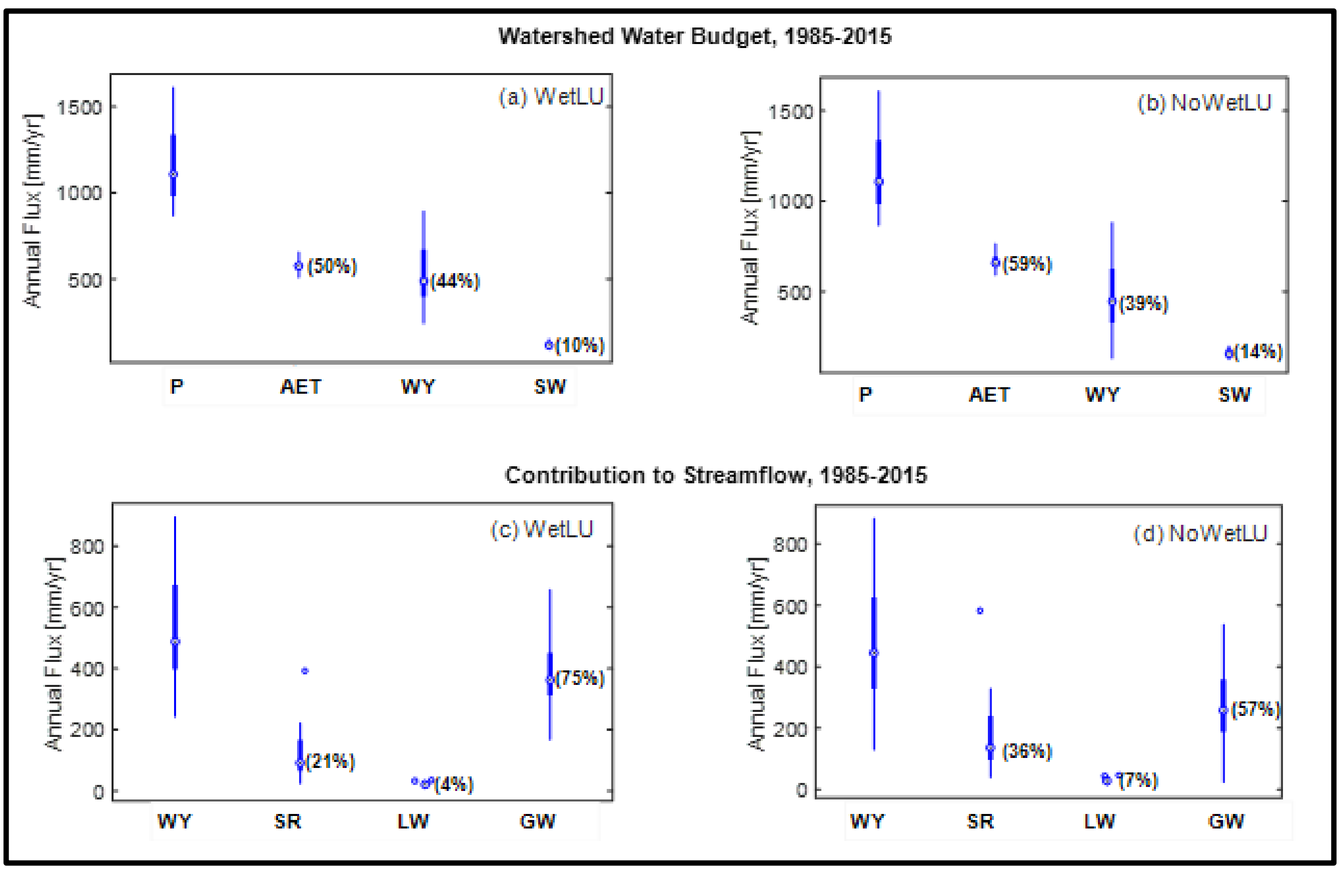


Fig 12. The 30-year average impact on the catchment water budget [a-b] and the streamflow generation process [c-d]

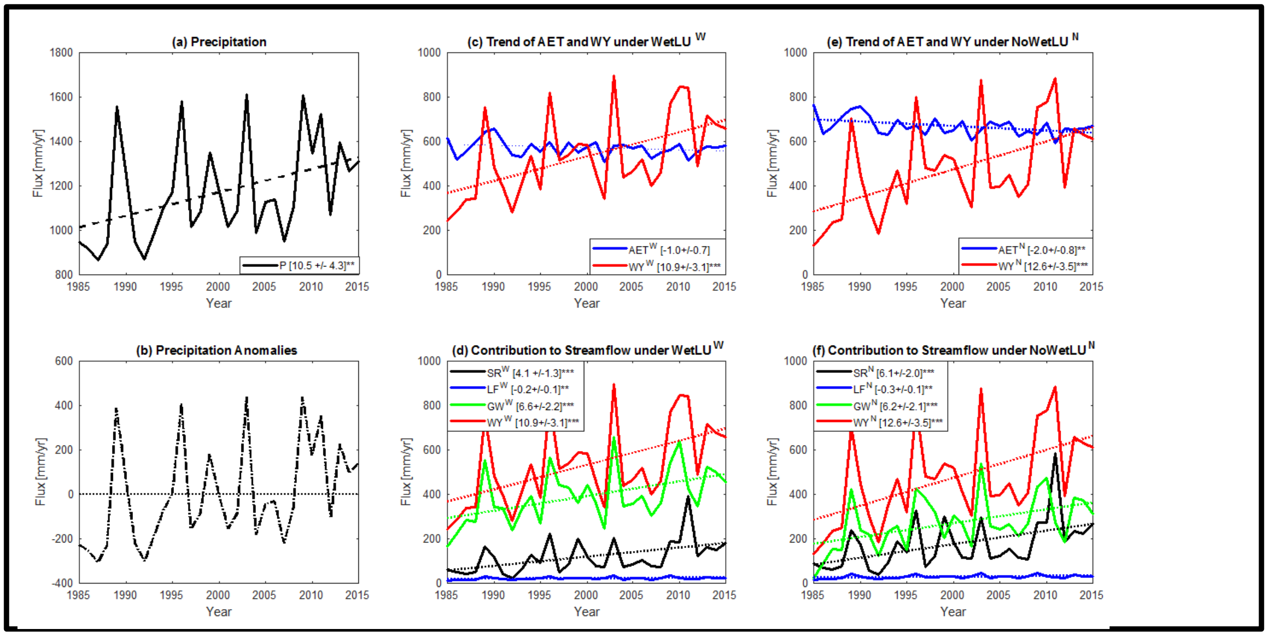


Fig 13. Inter-annual change trend in annual mean precipitation (a,b), the catchment water budget (c,e)] and the stream flow generation (d, f) with the presence [W] and absence [N] of GIWs.

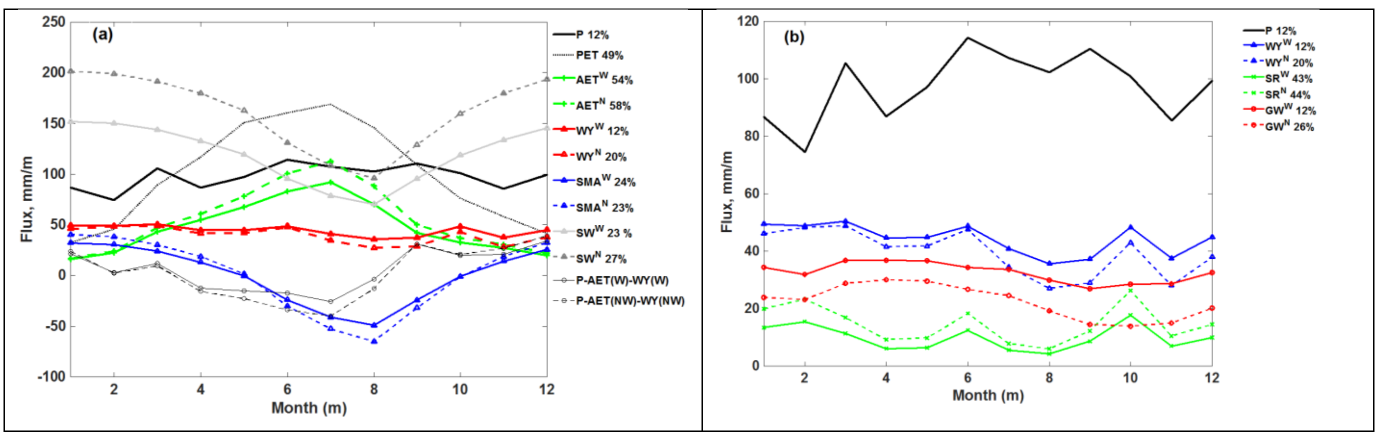


Fig 14. Seasonal variation in the catchment water budget (a) and the flow regime (b) under WetLU [W] and NoWetLU [N] scenarios.

Note: The statistical significance of the relationship is noted as: + significant at $\leq$0.15, * $\leq$ 0.1, ** at $\leq$ 0.05, and *** at $\leq$ 0.01. Those hydrological fluxes with the statistically significance linear trend (*p-value* < 0.05) are fitted with the straight line. The numeric values in the legend indicates the slope coefficient of the fitted line and the uncertainty (in mm/yr). All regression parameters were statistically significant with *p-value* <0.05, except AET^W. AET^W was the only hydrological variable which did not show any statistically significant linear trend (*p-value* > 0.15). The trend analysis was performed using both parametric and nonparametric methods using the annual mean simulation outputs over 1985-2015. Both methods showed very similar results. The superscript 'n' indicates no wetland (NoWetLU), and 'w' wetland (WetLU) scenario.

The terms in the legend are defined as: P = annual mean precipitation (mm/yr); AET=actual evapotranspiration (mm/yr); WY=water yield (mm/yr); SR=surface runoff (mm/yr); LW=subsurface lateral flow (mm/yr); and GW=groundwater flow (mm/yr).

(2) Reasons why established goals were not met, if appropriate:

We have met most of the project goals and extended the project scope. However, there were unexpected delay due to change in personnel (post-doc) and new hiring, relocation of the PI, etc. In addition, we changed and extended project scopes: (1) we expanded our work for the regional mapping and longer time series. We spent significant efforts to improve the statistical framework that can allow us to select unbiased, large samples and training data, as it would generate more reliable outputs with accuracy information. Data collection and processing of historical aerial images and Landsat records, and digitization of multiple land cover types took significant efforts and caused delay. (2) much more significant efforts have been made on our modeling tasks. Now our modeling objective was extended to assess hydrological function of wetlands, denitrification effects of wetted soils, and the effectiveness of management practices in wetland dominated catchment. Due to the serious shortcoming of existing wetland modeling, we continued our effort to improve the complex, process based model, SWAT's capability. First of all, we are improving its capacity to simulate the hydrological function of riparian wetlands at the landscape and catchment scales. Secondly, we also worked to develop integrative approach to inform the model using the inundation maps. The introduction and implementation of new concepts with new dataset took more efforts than planned. Third, we also developed new capability to represent N cycling in wetted soils, which improved intra-watershed responses of catchment model. Lastly, we are also assessing the effectiveness of best management agricultural practices on wetland dominated catchment using a physical model.

Our social components were extended to analyze the wetland permitting data in conjunction with the land cover change products and other socio-economic data sets. We collected last 30+ years wetland permitting data from all involved agencies and had to make considerable efforts to bring all data together and develop consistent database. These agencies did not have standardized format, records were incomplete, and some only had paper based information. The data gathering, processing, quality checking, and georeferencing these data were enormous task.

We also modified and calibrated the socio-economic land use change model (SLEUTH) for each county in Delmarva Peninsula, to idenfity the future urban growth and land development patterns and to assess their potential impacts on the current distributions of wetlands. Incorporating recent wetland trends reports and NWI wetland classes into SLEUTH, we attempted to locate those upland wetlands at a high risk to conversition to urban land. However, we found while *the SLEUTH model performed well in terms of capturing rates and patterns of historic urban development, it was not able to accurately simulate wetland conversion, a key component of wetland vulnerability on the Delmarva Peninsula*. Given the rarity of wetland occurrence and the relative rarity of urban change in the wetland dominated landscape, it is not surprising that the SLEUTH model was not able to effectively capture this aspect of wetland vulnerability at the local catchment scale.

(3) Other pertinent information including, when appropriate, analysis and explanation of cost overruns or high unit costs.

There is a higher unit cost on the personnel. As the project needs highly qualified personnel for wetland mapping component, the salary cost for the post-doc was much higher (costing ~ 40 k more, including salary, benefits, and overhead) than the original budget. The recent promotion of co-PI costed more to cover the time effort. The PI also internationally relocated in early 2015 and became a part-time researcher at UMD. *This new appointment setup restricted the amount of the time efforts to be charged regardless of the actual time effort that the PI spent, and this set-up delayed the spending as scheduled.* The remaining funding from the PI time effort (which could not be charged fully) was spent to support her travel back to US (1-2 times per last three project years, ~4 months in total; this was additional time effort she fully spent on this project in addition to her effort spent during the remaining project years), so that the PI could work closely with the Co-PIs and students to assure the successful completion and progress of this project.

(4) Collaboration with USDA and Shippensburg University.

Dr. Megan Lang, the Co-I from USDA, made significant contribution to this project. She was involved with data collection, mapping, physical modeling, and social aspect/policy analysis of this project. She was in the dissertation committee for the two graduate students (UMD) working on this project. Dr. Claire Jantz worked with her students to complete the wetland vulnerability assessment using SLEUTH and served on the dissertation committee for the Ph.D student who investigated the impacts of wetland policy on wetland loss and changes. Our team has a very good collaboration and communication. All of research activities, starting from research design, progress, and outcomes were shared on the weekly basis through multiple emails and regular face to face meetings. This close collaboration greatly benefitted our project progress.

(5) Summary of the project outcomes (including achievement made by Co-Is and collaborators)

The quantifiable project outcomes are presented as a form of peer reviewed journal articles (published, accepted, submitted), peer reviewed full conference papers, and Ph.D. dissertations below. In total, we produced 10 refereed articles in high impact journals, 3 papers under review, 4 referred full conference proceeding papers, and 2 Ph.D. and 2 MS theses at the conclusion of this research project.

Refereed Journal Articles:

1. Lee S., I.-Y. Yeo, M.W. Lang, A.M. Sadeghi, G.W. McCarty, G.E. Moglen and G.R. Evenson. 2018. Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. *Journal of Environmental Management* (accept subject to a very minor revision) (IF: 2.19)
2. Lee S, I.-Y. Yeo, Sadeghi A, McCarty G, Hively W, Lang M, Sharifi A. 2018. Comparative analyses of hydrological responses of two adjacent watersheds to climate variability and change using the SWAT model, *Hydrology and Earth System Sciences*, 22 689-708, https://doi.org/10.5194/hess-22-689-2018 (5-Year IF: 5.064, ranked 3/88 in Water Resources, Q1)
3. Lee S., Yeo I.-Y., Lang MW, McCarty GW, Sadeghi AM, Sharifi A, 2017, Improving the catchment scale wetland modelling using remotely sensed data, *Environmental Modelling and Software*, 10.1016/j.envsoft.2017.11.001 (In print; published online first) (5-Year IF: 4.979, ranked 3/27 in Ecological Modelling, Q1)
4. Lee S, Sadeghi AM, Yeo I.-Y., McCarty GW, Hively WD, 2017 Assessing the impacts of future climate conditions on the effectiveness of winter cover crops in reducing nitrate loads into the Chesapeake bay watersheds using the swat model, *Transactions of the American Society of Agricultural and Biological Engineers (ASABE)*, 60 1939-1955 (In print; published online first) (5-Year IF: 0.44, ranked 111/315 in Agricultural Biological Sciences –Agronomy and Crop Science, Q2)
5. Jin H, C. Huang, M. Lang, I.-Y. Yeo, SV Stehman. 2017, Monitoring of Wetland Inundation Dynamics in the Delmarva Peninsula using Time-Series Landsat Imagery from 1985 to 2011, *Remote Sensing of Environment* 190, 26-41, http://dx.doi.org/10.1016/j.rse.2016.12.001(5-Year IF: 7.653, ranked 2/29 in Remote Sensing, Q1)
6. Sharifi, A., M.W. Lang, GW McCarty, AM Sadeghi, *S Lee, H Yen, M. Rabenhorst, J. Jeong, I.-Y. Yeo, 2016, Improving model prediction reliability through enhanced representation of wetland soil processes and constrained model auto calibration–A paired watershed study, *Journal of Hydrology* 541, 1088-1103, http://dx.doi.org/10.1016/j.jhydrol.2016.08.022 (5-Year IF: 4.043, ranked 6 of 88 in Water Resources, Q1)
7. Lee, S, I.-Y. Yeo, A. Sadeghi, G. W. McCarty, W. D. Hively, M. W. Lang. 2016. Impacts of Watershed Characteristics and Crop Rotations on Winter Cover Crop Nitrate Uptake Capacity within Agricultural Watersheds in the Chesapeake Bay Region, *PlosOne*, http://dx.doi.org/10.1371/journal.pone.0157637((5-Year IF: 3.39, 15 of 64 in Multidisciplinary Sciences, Q1)
8. Yeo, I.-Y., S. Lee, A.M. Sadeghi, P.C. Beeson, W.D. Hively, G.W. McCarty, M. W Lang. 2014. Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model, *Hydrology and Earth System Sciences*, 18, 5239-5253, doi:10.5194/hess-18-5239-2014, 2014 (5-Year IF: 4.292, ranked 4/89 in Water Resources, Q1)

9. Huang, C., Y. Peng, M. Lang, I.-Y. Yeo, G. McCarty, 2014. Wetland inundation mapping and change monitoring using Landsat and airborne LiDAR data. *Remote Sensing of Environment*, 141, 231-242, doi: 10.1109/JSTARS.2013.2265191 (5-Year IF: 7.653, ranked 2/29 in Remote Sensing, Q1)
10. Lang, M., G., McCarty, R., Oesterling, I.-Y. Yeo. 2013. Topographic indices for improved mapping of forest wetlands, *Wetlands*, 33, 141-155, doi: 10.1007/s13157-012-0359-8 (5-Year IF: 2.002, ranked 142/229 in Environmental Sciences, Q3)

Paper under review:

11. Lang, M., V. Kim, G.W. McCarty, X. Lia, I.-Y. Yeo, C. Huang. Enhanced Detection of Inundation below the Forest Canopy using Multi-Return LiDAR Intensity Data, *Wetlands Ecology and Management* (under review)
12. Yeo I.Y., M. Lang, S. Lee, C. Huang, G.W. McCarty, A.M.Sadeghi, O. Yetemen. Mapping the landscape-level hydrological connectivity of headwater wetlands to downstream waters: a geospatial modeling approach - Part I. *Science of the Total Environment* (under review)
13. Yeo I.Y, S. Lee, M. Lang, O. Yetemen, G.W. McCarty, A.M. Sadeghi, G. Evenson. Mapping landscape-scale hydrological connectivity of headwater wetlands to downstream water: a catchment modelling approach - Part 2. *Science of the Total Environment* (under review)

Refereed Conference Papers:

14. Yeo, I-Y., Lang, M., Lee, S., Huang, C., Yetemen, O. 2017. Evolution of wetland monitoring from inventory to functional assessment and modelling: a case study from a US catchment. In Chiew F. and Vaze J. (eds). MODSIM2017, 22nd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2017, pp. 1537-1573. ISBN: 978-0-9872143-7-9. https://www.mssanz.org.au/modsim2017/L1/yeo.pdf
15. Lee S, Sadeghi AM, Yeo, I-Y, McCarty GW, Hively WD, Lang MW, Sharifi A, Assessing climate change impacts on winter cover crop nitrate uptake efficiency on the coastal plain of the Chesapeake Bay Watershed using SWAT model, 2017 ASABE Annual International Meeting. Spokane, Washington, July 16-19, 2017. doi:10.13031/aim.201700174
16. Sadeghi, A., Lee, S, Yeo, I-Y**,** G. W. McCarty, M. W. Lang. 2016. Inclusion of Riparian Wetland Module (RWM) into the SWAT Model for Assessment of Wetland Hydrological Benefit, 21st Century Watershed Technology Conference and Workshop sponsored by American Society of Agricultural and Biological Engineers (ASABE), Dec 3-9, 2016. doi: 10.13031/wtcw.2016003.
17. Lee, S, Yeo, I-Y, Sadeghi, A., McCarty, G. W., Hively, W. D., Lang, M. 2015. Prediction of climate change impacts on agricultural watersheds and the performance of winter cover crops: Case study of the upper region of the Choptank River Watershed, American Society of Agricultural and Biological Engineers (ASABE). 1st Climate Change Symposium: Adaptation and Mitigation Proceedings, Chicago, IL, May 3-5 2015. doi:10.13031/cc.20152123528.

Ph.D. Dissertation and MS Thesis (educational outcome):

18. Quentin A Stubbs, 2016. *A spatial-temporal analysis of wetland loss and section 404 permitting on the Delmarva Peninsula from 1980-2010*. Ph.D. Dissertation, University of Maryland
19. Sangchul Lee, 2017. *The integration of remotely sensed data into a watershed modelling approach to characterize winter cover crop nitrate update and wetland inundation at the landscape scale*. Ph.D. Dissertation, University of Maryland
20. Gary Greening, 2017. *Land use changes and wetland policy in Maryland*, Shippensburg University
21. Dana Heston, 2017. *Compilation of socio-economic data and GIS data analysis*, Shippensburg University