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Enhancing Landscapes for Sustainable Intensification and Watershed Resiliency

Tifton, Georgia
November 16–19, 2020

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Proceedings of the Seventh Interagency Conference on Research in the Watersheds

Enhancing Landscapes for Sustainable Intensification and Watershed Resiliency

Tifton, Georgia
Virtual Conference

November 16–19, 2020

Editors: James S. Latimer, David D. Bosch, John Faustini, Charles R. Lane, and Carl C. Trettin

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Abstract

These proceedings contain full-length papers, extended abstracts, and research abstracts of oral presentations and posters given at the Seventh Interagency Conference on Research in the Watersheds (7th ICRW)— Enhancing Landscapes for Sustainable Intensification and Watershed Resiliency, jointly hosted by the USDA-ARS and the University of Georgia, Tifton, GA, and held virtually November 16–19, 2020.

The 7th ICRW focused on the science and management of increased human and natural drivers of watershed change throughout the United States. The conference was structured to present, and address, key scientific and management issues faced by watershed managers and scientists throughout the U.S. Research was presented by Federal, State, and local scientists, academics, and non-governmental organizations focusing on managing complex watershed systems and watershed components (e.g., streams, rivers, lakes, estuaries, etc.). Thematic areas included watershed modeling, responses to climate related change, management strategies, integration of science and management, water quality and quantity, long-term agroecosystem science, as well as ecosystem-specific themes such as coastal plain watersheds and wetlands.

The conference was hosted by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), with material and in-kind support from the following organizations: Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), the USDA Forest Service, the U.S. Geological Survey, the U.S. Bureau of Land Management, the U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency, NASA, the U.S. Department of Energy, and the University of Georgia.

The 7th ICRW was built on the foundation laid by the previous hosting organizations: USDA Agricultural Research Service (2003), USDA Forest Service (2006 and 2015), U.S. Geological Survey and CUAHSI (2009), the Bureau of Land Management and National Park Service (2011), and U.S. Environmental Protection Agency (2018). The 8th ICRW will be hosted by the U.S. Geological Survey in Corvallis, Oregon. The conference is planned for June 2023.

Keywords: watershed modeling and conservation, coastal habitats, coastal watersheds, extreme climatic events, evapotranspiration, hydrologic modeling, land use, monitoring, stream and river networks, transboundary waters, watershed management, watershed science.

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Acknowledgments (continued)

Session Moderators

- **Agency and Organization Plenary: Current Research and Emerging Opportunities**
  Chair: Randy Fowler
- **Bedrock Flow and Reactions: Implications for Ecohydrology and Watershed Exports, Special Session (Invited)**
  Chair: Bhavna Arora and Ben Gilbert
- **Remote Sensing of Watersheds and Riparian Systems**
  Chair: Mike Cosh
- **Watershed Modeling (A)**
  Chair: David Goodrich
- **CEAP: Conservation Effects Assessment Project**
  Chair: Lisa Duriancik
- **Coastal Plain Watersheds**
  Chair: Steve Golladay
- **Watershed Response to Intensifying Precipitation Extremes and Adaptation Strategies: Science and Management Challenges, Special Session (Invited)**
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- **Poster Session**
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  Chair: Dipankar Dwivedi and Kimberly Ann Kaufield
- **FACETS: Floridan Aquifer Collaborative Engagement for Sustainability, Special Session (Invited)**
  Chair: Wendy Graham
- **Water Quality and Quantity (A)**
  Chair: Carl Trettin
- **Watershed Modeling (B)**
  Chair: Jeff Chanat
- **Long-Term Agroecosystem Research**
  Chair: Oliva Pisani
- **Water Quality and Quantity (B)**
  Chair: Doug Burns
- **Watershed Evapotranspiration in a Changing Environment, Special Session (Invited)**
  Chair: Ge Sun and Devendra Amatya
- **Integrating Science and Watershed Decision Making**
  Chair: Rick Webb
- **Watershed Response to Change**
  Chair: Elizabeth Keppeler

The organizers would like to thank all the additional unnamed individuals, including the conference participants and presenters, for helping to make the Seventh ICRW such a success.

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Converting naturally regenerated mixed pine-hardwood to loblolly pine plantation forests reduces streamflow in the Piedmont of North Carolina

Johnny Boggs, Ge Sun, and Steven McNulty
USDA Forest Service

There were almost no pine plantations in the southern United States in the 1950s. Now there are over 39 million acres of planted pine with most of that expansion occurring over the last twenty-five years to meet the rising demand for wood. Land management practices that include species conversion can have consequences to surface water availability by altering total forest transpiration. In 2010, two mixed-pine hardwood watersheds located in two different North Carolina Piedmont basins (i.e., Carolina Slate Belt, (CSB) and Triassic Basin, (TB)) were clearcut. In 2010, loblolly pine (Pinus taeda) was planted in the CSB watershed and shortleaf pine (Pinus echinata) was planted in the TB. Plot-level basal area measurements and continuous streamflow were monitored in each watershed to quantity how streamflow changed following the conversion from mixed-pine hardwood to pine. The CSB soils are thick, well-drained, and tend to function in a similar capacity across seasons. Conversely, the TB soils are thin, with a confining clay layer 30cm below ground surface, and are more prone to stormflow generation than CSB particularly in nongrowing seasons. We found that annual water yield increased by 260% in the CSB and 250% in the TB one year after the clearcut. However, yield decreased in subsequent years due to a rapid growth of the planted pines. By 2019, annual water yield was 6% less in the CSB than if the hardwood trees had not been cut. Despite the different soils, changes in basal and species are a more powerful regulator of annual hydrology in these ecosystems. This study is ongoing and the growth of the young pine trees will continue to be linked to streamflow measurements. Data from this project will help public and private landowners decide how to most effectively sustain forest and water resources together with silvicultural activities across the Piedmont region. Study results also have important implications to evaluate the role of vegetation in regulating storm runoff in the rapidly urbanizing Piedmont region in the southern U.S.

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Utilizing modeling to better understand habitat impacts

Chelsea Smith, Steven Brantley, Jill Qi and Stephen Golladay
The Jones Center at Ichauway

Over the past two decades the southeastern United States has experienced multiple severe to exceptional droughts that have been further compounded by human water demand through population growth, agricultural needs and other land-use changes. Water consumption by irrigated row crops and forest evapotranspiration (ET) are the largest water users within the Apalachicola-Chattahoochee-Flint (ACF) basin. Recent models have examined how reducing agricultural irrigation and converting fire-suppressed mixed pine/hardwood forests to longleaf pine affects streamflow within a sub-basin of the ACF (Ichawaynochaway Creek). While increases in flow are positive steps in alleviating ecological stress, understanding how flow relates to imperiled habitats during dry periods is crucial. Using survey techniques, specific elevation profiles of four shoals were generated to equate changes in flow to changes in habitat inundation at each shoal near a long term USGS gage used in the above models. These data allow us to examine how small changes in flow might affect available habitat both for small organisms such as macroinvertebrates as well as fish. We focused on the dry (25th percentile) and extremely dry (5th percentile) ranked mean monthly flows where the largest relative changes in flow were seen. Inundation percentage was similar among varying reductions in agriculture from 30% to 70% with a mean increase of 4.72% habitat. Inundation change was significantly higher when a combination of 30% agricultural reduction and longleaf pine restoration were combined with a mean increase 17% in the extremely dry months. Examining water depth capable of fish movement (>14 cm), similar patterns were seen with an average agricultural increase of 4.89% and agriculture plus pine combination at 23.85%. There was no significant difference in inundation during months at the 25th percentile as shoal habitat was above 80% available at these flow levels before simulations. Understanding how increases in the amount of water available in a watershed with changing land-use correlates to improvements in habitat is critical to finding watershed management solutions that serve both ecological needs and human water demands.

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Benefits of State and Private Forest Lands for Water Supply in the Southern United States

Ning Liu, University of Minnesota and USDA Forest Service; **G. Rebecca Dobbs,** North Carolina State University and USDA Forest Service; **Peter Caldwell,** USDA Forest Service; **Chelcy Ford Miniat,** USDA Forest Service; **Paul V. Bolstad,** University of Minnesota; **Stacy Nelson,** North Carolina State University; **Ge Sun,** USDA Forest Service

Forests provide the most stable and highest quality waters among all land uses. The southeastern U.S. is heavily forested and most of the forests are owned and managed by state and private entities, thus it is critical to understand the role of forested lands in providing water across the region, the fastest growing in the nation. Here we quantified surface water supply originating on State and Private Forest (SPF) lands in the 13 southern states at the 12-digit Hydrologic Unit Code watershed scale, using the Water Supply Stress Index (WaSSI) hydrologic model. Water originating on seven forest ownership types was tracked through the river network and linked to a database of surface drinking water intakes to estimate the population served by water from SPF lands across the southeast. We found that SPF lands in the 13 southern states comprised 44.2% of the total land area and contributed 44.3% of the 836 billion m^3 yr^{-1} total available water supply in the region. Of the 7,582 surface water intakes in the study area, 6,897 (91%) received some portion of their water from SPF lands, while 4,526 intakes (66%) received more than 20% of the water from SPF lands. Approximately 55 million people in the southeast, and 1.8 million people outside the 13 southern states, derived some portion of their water supply from SPF lands. These results highlight the importance of southern State and private forests in providing drinking water to downstream communities.

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Caveat to using the Large Woody Debris Index to assess degrading streams

Rebecca Fanning, College of Charleston
and Joshua Robinson, Robinson Design Engineers

The legacy effects of deforestation, row-crop cultivation, beaver extirpation, and removal of instream structural components such as river rock and log jams have permanently altered the fluvial geomorphology of watersheds across the Southeastern Piedmont region of the US. Contemporary research on log pieces and log jams as structural interventions capable of reversing stream incision has considerably influenced stream restoration methods in other parts of the United States. In the arid Southwest, for example, Beaver Dam Analogs (BDAs) and Post Assisted Log Structures (PALS) sometimes combined with beaver reintroductions have significantly improved the hydrological and ecological integrity of restored streams. Many of these methods draw from designs adapted in the early 1900's by the Forest Service and Soil Erosion Service. While these practices have enjoyed a renaissance in the western US, their application to the unique environmental legacies of the southeast are underrepresented in the literature and in practice. Hand-built wooden structures offer tremendous potential to reverse stream incision in the Southeast, where legacy erosion perpetuates a state of Riparian Hydrologic Drought.

We employed the Large Woody Debris Index (LWDI) to assess naturally occurring logs and log jams in South Carolina streams to compare a degraded 1200-acre tributary system of Minkum Creek in Gaffney to a recovering reference watershed within Kings Mountain National Military Park. Logistic regression of reference condition stream channel dimensions was used to establish impairment ratios that estimate the degree of channel incision and widening within the Minkum Creek stream network. We found that streams with 'functioning' LWDI scores suffered significantly higher depth impairment ratios than streams with 'not functioning' LWDI scores ($p = .0522$). Moreover, 'functioning' streams had statistically significant channel top-width impairment ratios compared to both 'not functioning' ($p=0.0644$) and 'functioning at risk' ($p=0.0546$) categories of stream reaches. Our findings suggest that 'functioning' LWDI scores indicate a stream reach is evolving on a trajectory from incising to widening. Thus, the functional categories of the LWDI are misleading and should not be employed as success criteria for stream restoration activities utilizing engineered log jams to reverse degradational processes in streams.

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Determining functional lift in restored Coastal Plain headwater streams in Little Pine Knot Watershed in Western Georgia

Stacey Sloan Blersch, CSU Earth and Space Sciences; **Kirsten Walsh,** CSU Earth and Space Sciences; **Sara Gottlieb,** TNC in Georgia

Over 30,000 dams currently exist in Georgia, many of which no longer serve their intended purpose, resulting in a significant loss of ecosystem services, including carbon sequestration, erosion regulation, and water purification. In August 2019, Columbus State University (CSU) began partnering with The Nature Conservancy (TNC) in Georgia to evaluate baseline conditions on two second order tributaries of Upatoi Creek near Ft. Benning, Georgia – Little Pine Knot Creek and Juniper Creek. Two earthen dams are scheduled for removal and by January 2020 in order to restore stream connectivity, reduce downstream sedimentation, and improve aquatic habitat at these locations. Functional assessment results from Summer and Fall 2019 will be presented based on continuous measurements of whole ecosystem metabolism using HOBO Dissolved Oxygen Data logger and HOBO temperature and light sensors. Hydrogeomorphic classifications of each creek and reference sites will also be discussed, providing a baseline for evaluating shifts in plant species composition over time.

Lower costs of monitoring equipment and ease of deployment makes ecosystem metabolism a viable metric to evaluate watershed management strategies long-term, as well as meet permitting requirements to show functional lift. While functional lift pre- and post-restoration were the intended purposes of this study, these methods can also be used to potential evaluate land-based management activities, such as the impacts of burning on carbon cycling through these headwater streams as a result of scheduled burns of longleaf pine forest ecosystems.

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Agricultural intensification and erosion control through land and water management practices in the watershed villages of Mali

Birhanu Zemadim Birhanu, Kalifa Traore, Karamoko Sanogo, Ramadjita Tabo, Gundula Fischer, and Anthony Michael Whitbread

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

Land and water management practices have been widely implemented in rural Mali since the 1980s to improve agricultural productivity and erosion control. One of the most common land and water management practice applied in the central and southern parts of rural Mali is contour bunding (CB). In this study the impact of CB technique was evaluated based on defined sets of sustainable agricultural intensification domains. Field experimentation involved implementation of contour lines with farm ridges, agronomic trails, and runoff and erosion measurements. Agronomic data was collected on sorghum, maize, groundnut and millet for three consecutive years (2015 to 2017). Runoff and erosion data were collected and soil nutrients analysis were conducted at the Institut d'Economie Rurale (IER) in Mali. Data on social, economic and human well-being was obtained from individual farmer surveys. CB involves the layout of contour lines with land leveling devices to identify points of equal elevation and construction of contour lines with draught animals and human labor. Majority of the labor input to construct and maintain the CB comes from adult men who are head of the household (58%) and youth male (33%). Results indicated that with the application of CB yield of crops was statistically higher with the highest increase in grain yield and biomass obtained for maize and millet ($p<0.01$). CB application was useful in retaining soil water and reduced erosion rate. In treatment fields, 162 mm of rainfall per year was saved as soil moisture and on average 13,090 ton per hectare of soil was lost from farm fields without CB and CB implementation significantly reduced the soil loss by 163% ($p<0.01$). The improvements in crop yield and biomass, and the retention of soil nutrients positively changed household livelihood conditions. Majority of farmers (78%) witnessed better income from the sale of crops grown on CB plots and made them to be food secure.

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A synthesis of ecosystem management strategies for forests in the face of chronic nitrogen deposition

Christopher M. Clark, U.S. Environmental Protection Agency; **Jennifer Richkus,** RTI International; **Phillip W. Jones,** RTI International; **Jennifer Phelan,** RTI International; **Douglas A. Burns,** U.S. Geological Survey; **Wim de Vries,** Wageningen University and Research; **Enzai Du,** Beijing Normal University, Beijing; **Mark E. Fenn,** USDA Forest Service; **Laurence Jones,** Centre for Ecology & Hydrology; **Shaun A. Watmough,** Trent University

High levels of atmospheric nitrogen (N) deposition may have deleterious effects on terrestrial and aquatic ecosystems. If N deposition exceeds the uptake capacity of forested ecosystems, enhanced N loads to fresh waters may results and contribute to problems such as estuarine eutrophication. Although N deposition has declined in much of North America and Europe since the 1990s, these decreases may be insufficient to induce recovery from decades of elevated deposition, suggesting that management interventions may be necessary to promote recovery and to achieve reduced N loads from forested ecosystems. Here, we review the effectiveness of four remediation approaches (prescribed burning, thinning, liming, carbon addition) on three indicators of recovery from N deposition (decreased soil N availability, increased soil alkalinity, increased plant diversity), focusing on literature from the U.S. We reviewed papers indexed in the Web of Science since 1996 using specific key words, extracted data on the responses to treatment along with ancillary data, and conducted a meta-analysis using a three-level variance model structure. We found 69 publications (and 2158 responses) that focused on one of these remediation treatments in the context of N deposition, but only 29 publications (and 408 responses) reported results appropriate for meta-analysis. We found that carbon addition was the only treatment that decreased N availability (effect size: -1.80 to -1.84 across metrics), while liming, thinning, and prescribed burning all tended to increase N availability (effect sizes: +0.4 to +1.2). Only liming had a significant positive effect on soil alkalinity (+10.5% to +82.2% across metrics). Only prescribed burning and thinning affected plant diversity, but with opposing and often statistically marginal effects across metrics (i.e., increased richness, decreased Shannon or Simpson diversity). Thus, it appears that no single treatment is effective in promoting recovery from N deposition, and combinations of treatments should be explored. These conclusions are based on the limited published data available, underscoring the need for more studies in forested areas and more consistent reporting suitable for meta-analyses across studies.

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Riparian land cover and hydrology influence stream dissolved organic matter composition in an agricultural watershed

Oliva Pisani, David D. Bosch, Alisa W. Coffin, Dinku M. Endale, Dan Liebert, Timothy C. Strickland

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Dissolved organic matter (DOM) represents an essential component of the carbon cycle and controls biogeochemical and ecological processes in aquatic systems. The composition and reactivity of DOM are determined by the spatial distribution of its sources and its residence time in a watershed. While the effects of agricultural land cover on DOM quality have been reported across spatial scales, little is known about how this relationship can change over time. Furthermore, the influence of riparian land cover on stream DOM composition has received little attention. To this end, a multi-year (2016-2018) DOM characterization study was conducted using bi-weekly water samples collected from seven sub-watersheds nested within the Little River Experimental Watershed (LREW) near Tifton, Georgia, USA. DOM optical properties were determined to assess compositional variations using UV-Vis and excitation-emission matrix (EEM) fluorescence spectroscopy coupled with parallel factor (PARAFAC) analysis. PARAFAC analysis indicated that DOM in the LREW was dominated by three humic-like fluorescing components of terrestrial, microbial, and anthropogenic origin and a protein-like component. DOM composition was influenced by land cover, and shifted towards recently produced, low molecular weight DOM with low aromaticity as the percentage of agricultural land within riparian wetlands increased. The optical properties of DOM were dominated by recently produced, microbial-derived material during low discharge and low baseflow periods. The results of this two-year study indicate that the replacement of forested riparian buffers with agricultural land can result in altered DOM composition which may affect carbon cycling and downstream water quality in agricultural watersheds.

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Section 2: Watershed Evapotranspiration in a Changing Environment, Special Session

Estimating daily and seasonal evapotranspiration of a southeastern U.S. Atlantic coastal plain forest

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We tested an empirical method to estimate daily actual evapotranspiration (AET) of a forested watershed in coastal South Carolina using measured daily shallow soil moisture (SM) and potential ET (PET) estimated using weather data by two methods, i) Penman-Monteith (P-M) and ii) Priestley-Taylor (P-T), and soil field capacity during the 2015–2016 period. This work was motivated by Domec and others (2012), who found the measured annual and monthly AET by the SM and water table fluctuation methods agreed to within 10 to 20 percent of the ET from eddy covariance measurements for a managed pine forest in coastal North Carolina. Our study site is a 160-ha control watershed (WS80) (33.15° N; 79.8° W) in the paired system within the Santee Experimental Forest on the Francis Marion National Forest in coastal South Carolina (fig. 1a). This low-gradient (slope < 3 percent) watershed is on moderately well to poorly drained soils, with a restrictive layer around 2.0 m depth (Harder and others 2007). Loblolly pine (*Pinus taeda*)-mixed hardwoods, naturally regenerated since Hurricane Hugo (1989), dominate the

Figure 1—Location map (a) of the study watershed (WS80) (red outline). Pictured monitoring components are (b) rain gauge, (c) flow gauging station with a compound weir outlet, (d) weather station above forest canopy, (e) soil moisture sensors and datalogger, (f) recording groundwater well, and (g) sap flux sensors in trees at Santee Experimental Forest in coastal South Carolina.

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watershed, with the watershed-wide average annual leaf area index of 2.9 m^2 m^{-2} (Dai and others 2013). The site average daily temperature and annual rainfall are 17.8 °C and 1370 mm, respectively (Dai and others 2013).

Rainfall data were collected using automatic gauges backed up by a manual gauge (fig. 1b). A gauging station with a compound V-notch/flat weir (fig. 1c) was instrumented to measure stream stage on a 15-minute interval to compute outflow rates using an established rating curve. An on-site above-canopy tower weather station collected data on a 15-minute basis (fig. 1d). Soil hydraulic parameters for the dominant Wahee soil and additional details of hydrologic monitoring can be found elsewhere (Amatya and Trettin 2021, Harder and others 2007).

We computed monthly AET, as a residual in water budget, as Rainfall – interception – streamflow – change in storage, for the 2015–2016 period. Deep seepage was assumed negligible in this shallow system with a restrictive horizon (Harder and others 2007). Interception was estimated as 11 percent of rainfall (Harder 2004). Change in storage (ΔS) for each month was computed from a) limited hourly soil moisture (SM) measured (fig. 1e) at only a shallow 10-cm depth in three plots, which was averaged (SM-ΔS) and assumed to be representative up to 80 cm depth in this shallow system; and b) measured hourly water table depth (fig. 1f) (WT-ΔS) with average drainable porosity (0.05) (Harder and others 2007) (table 1). The limited SM and sap flux measurements (fig. 1g) were collected as a part of the Forest Service, U.S. Department of Agriculture (USDA), project on Remote Assessment of Forest Environmental Stressors (RAFES).

Daily AET for the site was independently calculated following Fisher and others (2005) as AET = f * PET, where f = SM/FC, and FC = soil moisture content at 10 kPa estimated from soil water characteristic data (Harder and others 2007). Daily PET was computed using the P-M and P-T methods with the measured daily weather data (Amatya and Harrison 2016). The method assumes daily AET = PET when the SM ≥ FC, otherwise AET = PET * SM/FC. Monthly AET, summed from daily values using each of the two PET methods, was compared with the AET as residual in the water budget (table 1). AET from each of the PET methods was also tested to predict monthly streamflow as residual in the water budget.

Both the 2-year mean monthly WT-ΔS (-0.5 mm) and WT-AET (83.6 mm) were not different ($\alpha = 0.05$) from the SM-ΔS (-0.7 mm) and SM-AET (83.9 mm), respectively, with $R^2 = 0.82$ between monthly ΔS and 0.72 between the respective monthly AET values. The mean monthly P-M AET was 92 percent of the P-M PET, dropping as low as 64 percent for May 2016 with lower rainfall and higher PET (table 1), potentially indicating a moisture stress. Results showed the R^2 and mean monthly difference in residual streamflow using each of the P-M and P-T AET methods and the observed data as 0.97 and -2.2 mm and 0.94 and 6.2 mm, respectively, indicating a better performance of the P-M PET method. Our analysis supports the WT-ΔS as a proxy for monthly SM-ΔS, as well as Fisher and others (2005) method for approximating the monthly AET on these poorly drained wetland forests, consistent with Domec and others (2012). However, the results may have been influenced by SM measurements only at a shallow depth.

Table 1—Measured/estimated monthly water budget components including Penman-Monteith (P-M) and Priestley-Taylor (P-T) PET for January 2015 to December 2016

Year-Month	Rainfall	Flow	SM-ΔS	WT-ΔS	SM AET	WTD AET	P-M AET	P-T AET	P-M PET	P-T PET
						mm				
2015-Jan.	134.1	71.5	8.1	1.3	39.8	46.5	32.5	26.5	32.5	26.5
2015-Feb.	118.8	64.8	27.6	2.3	13.3	38.6	33.2	30.6	33.2	30.6
2015-March	112.2	77.2	-24.8	-1.9	47.4	24.5	66.3	65.8	66.3	65.8
2015-April	70.6	6.7	-32.2	-3.4	88.4	59.6	90.1	92	91.8	93.7
2015-May	57.3	0.6	-104.3	-56.5	154.8	107	115.9	109.5	140.1	132.4
2015-June	213.9	3.3	62.6	44.4	124.5	142.7	152.1	131.8	179.6	155.2
2015-July	161.6	3.7	-22.3	-15.9	162.4	156	164	144.2	179	157.6
2015-Aug.	243	12.2	91.7	30.5	112.3	173.6	124.3	112.6	140.4	127.2
2015-Sep.	136.8	8.6	-10.9	0.2	124	112.9	87.1	81.2	94.7	88.1
2015-Oct.	666.7	598.9	39.4	-1.2	-5.1	35.5	61.2	58	61.2	58.1
2015-Nov.	137.1	76.9	-20.4	-5.8	65.5	50.9	43.4	40.9	43.4	40.9
2015-Dec.	119.1	43.6	6	7.4	56.4	55	36.1	31.1	36.1	31.1
2016-Jan.	75	48.3	4.2	-0.1	8.8	13	30.8	25.1	30.8	25.1
2016-Feb.	169.2	127.9	-2.3	-2.2	25.1	25	41.6	43.5	41.6	43.5
2016-March	64.7	12.8	-9.2	-2.7	53.9	47.4	83.2	75.7	83.2	75.7
2016-April	38.1	2.4	-88.2	-38.6	119.6	70	115.3	108.1	120.4	113.1
2016-May	91.4	0	-14.7	-4.2	96	85.5	87	79	135.1	122.1
2016-June	183.8	1	5.2	25.5	157.4	137.1	135	119.5	176.2	155.9
2016-July	177.5	1.7	3	-11.1	153.2	167.4	154	133	191.5	164.5
2016-Aug.	252.7	36.8	43.8	15.1	144.3	173	143.1	142.6	147.2	146.6
2016-Sep.	246.8	64.4	68.5	19.7	86.8	135.6	99.6	94.8	99.8	95
2016-Oct.	295.7	234.4	-75.3	-35.3	104	64	82.6	59	83.3	59.5
2016-Nov.	15.7	0	-53	-38.1	67	52.1	45.9	23.9	54.5	28.3
2016-Dec.	132.4	24.4	80.3	59.3	13.1	34.1	32.2	14.9	33.7	15.5
2015 Sum	**2171.2**	**968**	**20.4**	**1.5**	**983.7**	**1002.8**	**1006.3**	**924.2**	**1098.2**	**1007.1**
2015 Mean	**180.9**	**80.7**	**1.7**	**0.1**	**82**	**83.6**	**83.9**	**77**	**91.5**	**83.9**
2016 Sum	**1743**	**554.2**	**-37.7**	**-12.6**	**1029.2**	**1004.2**	**1050.3**	**919.1**	**1197.3**	**1044.8**
2016 Mean	**145.3**	**46.2**	**-3.1**	**1**	**85.8**	**83.7**	**87.5**	**76.6**	**99.8**	**87.1**
2-yr Sum	**3914.2**	**1522.2**	**-17.3**	**-11.1**	**2012.9**	**2007**	**2056.6**	**1843.3**	**2295.5**	**2051.9**
2-yr Mean	**163.1**	**63.4**	**-0.7**	**-0.5**	**83.9**	**83.6**	**85.7**	**76.8**	**95.6**	**85.5**

Note: WTD AET and SM AET are the AET as a residual in water budget using change in storage (ΔS) estimated from water table drainage volume (WT-ΔS) and measured soil moisture (SM-ΔS), respectively; P-M AET and P-T AET were obtained from independently estimated daily AET values using the approach of Fisher and others (2005) that uses PET, soil moisture, and soil field capacity; P-M and P-T are the Penman-Monteith and Priestley-Taylor based PET, respectively. The estimated annual sum of P-M AET values was greater than the sum of P-T AET values and was closer to water budget based AET (using either the SM-ΔS or WT-ΔS storage estimates) in both 2015 and 2016.

This preliminary study provides useful insights into yearly and monthly catchment water balance components of a forested wetland watershed in coastal South Carolina, USA. Among the tested methods with a short period of data including limitations of the SM measurements, application of the P-M model showed slight superiority over P-T when compared to *in-situ* AET estimates obtained as the water budget residual. The data collected in this study can be useful for validation of remote sensing-based shallow soil moisture and evapotranspiration products while the tested algorithms for AET have their application for further testing on an adjacent treatment watershed (WS77) undergoing longleaf pine restoration, as well as upscaling or development of large-scale water balance models. However, additional data collection for a longer period, primarily for soil moisture for deeper depths, on other soil types is highly recommended for reducing prediction uncertainties due to spatially distributed soil heterogeneities.

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Do riparian forests alter water uptake in response to flash droughts? Case study from Panola Mountain Research Watershed

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The term flash drought describes abnormally dry conditions that manifest over a relatively short period of time due to a combination of reduced precipitation, high temperatures, and increased solar radiation due to low cloud cover that increases evapotranspiration, resulting in reduced soil moisture and potential for vegetative stress. However, the negative impacts to vegetation may be mitigated in landscapes with shallow water tables. In this study, we evaluate the buffering role that groundwater may serve in reducing impacts from drought by sustaining water utilization of riparian trees.

This study was conducted at the Panola Mountain Research Watershed during a flash drought that occurred over the southeastern U.S. in late summer/fall 2019. Between August 6th and September 24th, the drought monitor degraded 3 classes, from no drought to D2 (severe drought). To evaluate possible impacts from the rapid drying, we examined sap flow data from 20 riparian trees to evaluate changes in water use that may indicate tree stress. Further, we used diurnal water table fluctuations (DWTF) in nine wells to assess the magnitude of water drawn from the saturated zone to support transpiration (TG).

Sap flow at all trees remained consistent throughout the period, responding to vapor pressure deficit and solar radiation but not showing a trend with increasing drought severity. In contrast, water-table fluctuations indicated that a greater quantity of water was sourced from the saturated zone at some wells. This pattern was not consistent across the riparian zone, likely owing to specific combinations of water table depth, rooting depth, and physiological adaptations. Comparing TG derived from DWTFs between September 2018 and September 2019, we observed greater TG at most wells in 2019, suggesting that as soil moisture is depleted, riparian vegetation extracts a greater volume of water from the saturated zone when possible. In riparian zones, and other areas with shallow water tables, groundwater likely sustains water utilization until drought becomes prolonged and the water table declines below the rooting depth. While riparian trees can benefit from shallow groundwater, this water uptake pattern can influence baseflow from low-order watersheds during flash droughts, potentially reducing streamflow for downstream uses.

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Spatially explicit evapotranspiration for improved characterization of basin water budget dynamics at multiple spatiotemporal scales

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The accurate estimation of evapotranspiration (ET) is vital in characterizing watershed water budget dynamics for understanding rainfall-runoff processes, water use and availability, and impact of drought on the ecosystem. With the availability of historical remote sensing data and gridded weather datasets, several ET algorithms have been developed that could produce ET maps at multiple spatiotemporal scales. The Operational Simplified Surface Energy Balance (SSEBop) is one such method that is being applied for generating seasonal and annual ET at 100 m (Landsat) and 1km (MODIS: Moderation Resolution Imaging Spectroradiometer) spatial resolution in diverse ecosystems around the world. Owing to differences in satellite spatiotemporal domains, Landsat and MODIS-based ET can bring complementary data and information for watershed science. For example, Landsat-scale ET provides higher spatial information for smaller watersheds where field scale hydrologic and water resources assessments are desired. On the other hand, MODIS-scale ET is adequate for basin-scale studies where aggregate summary by broad land cover types and landforms is needed. Furthermore, historical assessment of ET is now possible using Landsat which goes back to the early 1970s and 1980s for examining long-term trend analysis. The applications of both Landsat and MODIS-based ET will be presented for crop water use mapping, drought monitoring, and basin-scale water budget studies in diverse ecosystems around the world at multiple spatiotemporal scales.

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Effects of forest understory removal and prescribed fire on watershed water yield and evapotranspiration in the southern Appalachian Mountains, USA

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Climate change, disturbances, and forest management in the southern Appalachian mountain region have induced changes in canopy species composition and expansion of subcanopy shrubs (i.e., *Rhododendron maximum* L. and *Kalmia latifolia* L.). As a result, these forests are less resilient to drought and have reduced productivity, timber quality, water yield, and understory biodiversity. Forest managers need innovative management practices aimed at enhancing resilience and the provisioning of ecosystem services including a clean, reliable water supply. We evaluated the effect of one such management strategy on water yield and evapotranspiration using the paired watershed experimental design at the USDA Forest Service Coweeta Hydrologic Laboratory in the southern Appalachian Mountains. The riparian rhododendron understory was cut and slashed, and stumps were herbicided across the 37.8 ha treatment watershed in winter 2018, and a low severity prescribed fire was conducted in spring 2019. Thirty-tree years of pretreatment water yield and precipitation measurements in the treatment and adjacent 41.3 ha reference watersheds provided an excellent calibration ($R^2 > 0.99$), allowing us to quantify the effects of the rhododendron removal only in the first year and rhododendron removal plus prescribed fire in the second year after treatment. Rhododendron removal resulted in a significant water yield increase of 6.2 cm (3.0%) over what would have been expected had the treatment not occurred. Evapotranspiration (precipitation minus water yield) also decreased by 6.2 cm, a 5.8% change. Second year results including the effect of the prescribed fire using data collected through March 2020 are forthcoming and will be available at the time of presentation of our work. These results suggest that rhododendron removal followed by prescribed fire will likely decrease evapotranspiration and increase water yield, enhancing water supplies in the region. Future work will quantify the effect of the treatment on forest species composition and other ecosystem services including ecosystem productivity and biodiversity.

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Using ET estimated from remotely sensed data to investigate drought-induced tree mortality in a temperate forest in the Central U.S.

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Drought can have large impacts on forested ecosystems. Short-term drought can make forests more susceptible to insect attack, infection and wildfire, while long-term severe drought can directly cause catastrophic hydraulic disconnection that induces tree mortality. Evapotranspiration (ET) is a key parameter that links the hydrological and ecological processes and is an effective indicator of vegetation health. Mapping ET using satellite remote sensing data has been widely applied to study the spatial dynamics of water use at regional scales for decades. Surface energy balance methods, based on remotely sensed land surface temperature retrieved from thermal infrared imaging systems, are commonly used to map ET. In this study, we applied the ALEXI/DisALEXI (Atmosphere-Land Exchange Inverse model and associated flux disaggregation algorithm) energy balance modeling system over a drought-sensitive temperate forest in the Central US. to estimate 30 m daily ET from 2010 to 2014, including an extreme drought event that occurred in 2012. ET retrievals from multi-scale satellite sensors including Landsat and MODIS (Moderate Resolution Imaging Spectroradiometer) were fused to daily 30 m ET using STARFM (Spatial Temporal Adaptive Reflectance Fusion Model). This study area contains an AmeriFlux site (US-MOz), and has a good record of tree mortality data, especially after the 2012 drought. The model results were evaluated at the flux tower site and showed good agreement with observed fluxes. The actual-to-reference ET ratio (fRET) was also estimated and used as a vegetation stress indicator to investigate the relationship between evaporative stress and drought-induced tree mortality. We found a significant correlation ($R^2 = 0.52$) between tree mortality data in 2013 and fRET difference between pre-drought year (2010) and drought year (2011, 2012), which suggests a high correlation between drought-induced tree mortality and pre-drought forest health condition at the US-MOz site. This study demonstrated the capability of using remotely sensed ET metrics at high spatiotemporal resolution for monitoring forest water use and drought-induced tree mortality.

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Evapotranspiration: the Unsung Hero for Ecosystem Services

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The connections between ecosystem functions and services (water supply, flood control, climate moderation, carbon sequestration, biodiversity) have not been well recognized and studied, and the role of evapotranspiration (ET) is often underestimated. For example, ET rates generally exceed precipitation in the growing season and annual ET rates exceed runoff coefficients in natural watersheds in the southern U.S. Climate change affects watershed hydrology by directly (energy and water availability) and indirectly (species change, fire, insects and diseases) altering ET processes. Urbanization, a permanent form of land use change, affects watershed hydrology largely (in addition to increase in impervious surfaces) by reducing ET in the growing season in the humid North Carolina. Thus, accurately estimating ET is of paramount importance in global change studies that focus on quantifying the effects of land use change and climate change on land surface processes and ecosystem services. The ecosystem-level ET process is inherently complex due to the numerous controls by physical, chemical, climatic, and biological factors. The 'Paired watershed' approach has been traditionally used to quantify the role of forest vegetation cover and ET in affecting stream hydrographs for small watersheds. Fine-scale ecosystem ET flux is commonly measured together with energy and carbon flux (e.g., CO_2, CH_4) because these fluxes are highly coupled. However, quantifying ET for a large area is still costly and uncertain. ET science remains as an imprecise one. This paper uses case studies to demonstrate that ET is critical for understanding how land cover change and global warming affect stream peak flows, water yield, and ecosystem productivity. Current issues about quantifying ET by field measurements and modeling are discussed.

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Evaluating high water table hydrology and eddy covariance measurements of evapotranspiration at a newly instrumented watershed in coastal South Carolina

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A water table near the soil surface is common to southeastern U.S. coastal forested watersheds. The high water table creates a situation where soil moisture storage occurs in both saturated and unsaturated conditions. The position of the water table is both a reflection of the balance of precipitation and evapotranspiration and a control on portioning rainfall into ET and streamflow. Measuring ET has been the major limitation to understanding the interaction of evapotranspiration, saturated and unsaturated soil moisture storage, and streamflow in these watersheds. This paper will outline a newly instrumented watershed where an eddy-flux tower has been placed in a small (13 ha) forested headwaters watershed to measure atmosphere–vegetation exchange of water. Sub-canopy measures of light and throughfall, unsaturated soil moisture sensors and a grid of shallow wells measure water movement from the canopy to the groundwater system. The tower has been active since Jan 2019, and other measures were added during June and early July of 2019. The system was active during moisture drawdowns prior to, and after the site was hit by Hurricane Dorian, with over 220 mm of rainfall, in August 2019. We monitored the development of the area of saturated overland flow spread across the watershed during the storm and the retreat of that area as ET removed water from saturated storage in the months since the storm. Vegetation on the tower footprint has been measured using FIA phase 2 plots representing slightly over a 10% sample of the tower footprint (220 m radius) area. In addition large scale aerial photography has been used to map crowns and species composition across the footprint area. Longleaf pine dominates the eastern half of the footprint while a mixture of longleaf, loblolly, and pond pines are present in the western half. Following regulatory approval in February 2020, a Parshall flume was installed to measure streamflow. During the short period of operation we have seen water table drawdowns approaching 1 m and soil moisture ranging from saturation to near wilting point due to heavy rain and high PET.

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Stand-level transpiration increases after eastern redcedar encroachment into the Cross-timbers

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Eastern redcedar (Juniperus virginiana, redcedar) is encroaching into post oak (Quercus stellata)-dominated savannas and forest on the dry, western edge of the eastern deciduous forest of the USA (Cross Timbers). Redcedar is an evergreen tree that is both encroaching into canopy gaps and growing into the midstory, which results in changes in tree species composition, canopy structure, and phenology of the Cross Timbers. However, water relations and the hydrological impact associated with the deciduous oak forest's transition to an oak-juniper mixed forest remains unknown. Our objective was to determine leaf water potential, gas exchange, and stand-level transpiration and associate them with environmental variables and soil water stress. We quantified leaf-level gas exchange using a portable photosynthesis system (Li-6400, Li-Cor Inc, USA) and stand-level transpiration using sap flow systems (Dynamax Inc., Houston, TX, USA) for post oak, redcedar, and post oak and redcedar mixed stands with a similar total basal area for 20 months between May 2017 and December 2018 in a Cross-Timbers forest near Stillwater, Oklahoma.

Our results showed that post oak had greater gas exchange rates than redcedar during periods of high moisture, but both species had a similar reduction in leaf-level gas exchange during drought. Water potentials tended to be more negative in the pure redcedar stand compared to the mixed stand. The mean sap flow density of redcedar was usually higher than post oaks. A structural equation model demonstrated a significant correlation between sap flow density and shallow soil moisture for redcedar but not for post oak. At the stand level, the annual water use of the mixed stand was greater than the redcedar or oak stand of similar total basal area.

The transition of oak-dominated Cross-Timbers to redcedar and oak mixed forest will likely increase carbon and water exchange such that carbon sequestration increases but water availability for runoff or recharge to groundwater decreases. The change in canopy structure and the fuel load will have an important implication for wildfire management.

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Section 3: Integrating Science and Watershed Decision Making

Assessment and Decision Support for Natural Asset Management in Connecticut Coastal Watersheds to Meet Combined Water Quality and Biointegrity Goals

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The Clean Water Act emphasizes restoration and repair of dysfunctional (impaired) aquatic ecosystems caused by anthropogenic drivers, especially development, agriculture and climate change. But, addressing these multiple-driver causes, and managing the complex and pervasive mix of chemical, physical and biological pressures they deliver, remains a top science, management and policy challenge. Attaining ecosystem-level biointegrity targets requires an integrative and collective ecosystem context engendered in ecosystem-based management (EBM). This perspective is often lacking in single-stressor assessment and management protocols that commonly target only nitrogen or phosphorus; thus, more complex ecosystem outcomes that broadly support healthy watersheds and aquatic ecosystem goals are not assured.

The Biological Condition Gradient (BCG), recently consolidated in the 2016 EPA Practitioner's Guide, offers a scientifically-validated, EBM alternative that supports a whole ecosystem conceptual approach. Because watersheds and waterbodies are structurally and functionally diverse, health metrics vary with local conditions and levels of stress. BCG integrates watershed stressor effects along a gradient paired to aquatic biocondition. This provides a robust mechanism and appropriate context for site-specific benchmarking – an integrated, top-down approach to pairs overall watershed health, or condition, based on land-cover attributes to ecosystem-level outcomes of aquatic biointegrity, or biocondition, to guide watershed management.

To this end, I devised a scalable decision-support framework (DSF) using basic land cover data downloaded from UConn's CLEAR website for 160 coastal Connecticut sub-regional watersheds. Landscape asset management was guided by an index derived from the extent of natural cover in the watersheds and vegetated riparian buffers and used to set benchmarks that define the range of watershed and aquatic ecosystem conditions, targets and outcomes consistently with the BCG. The DSF tailors recommended land cover extent and buffer widths to watershed size and condition to meet the desired land-cover management target supporting biointegrity goals. Land-cover is easily translated into direct estimates of nutrient loads consistent with land cover management goals. The BCG and DSF applications provide a firm basis for nutrient-targeting, criteria-setting and Total Maximum Daily Load (TMDL) analyses, avoiding the uncertainties associated with back-calculating loads from highly-variable monitoring data. The DSF will be demonstrated for typical Connecticut coastal watersheds.

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Real-time coastal salinity index for monitoring coastal drought and ecological response to changing salinity values along the Gulf of Mexico and the Eastern Atlantic Coast

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Coastal droughts have a different dynamic than upland droughts, which are typically characterized by agricultural, hydrologic, meteorological, and (or) socio-economic impacts. Drought uniquely affects coastal ecosystems due to changes in salinity conditions of estuarine creeks and rivers. The location of the freshwater-saltwater interface in surface-water bodies is an important factor in the ecological and socio-economic dynamics of coastal communities. The location of the interface determines the freshwater and saltwater aquatic communities, fisheries spawning habitat, and the freshwater availability for municipal and industrial water intakes. The severity of coastal drought may explain changes in Vibrio bacteria impacts on shellfish harvesting and occurrence of wound infection, fish kills, harmful algal blooms, hypoxia, and beach closures. To address the data and information gap for characterizing coastal drought, a coastal salinity index (CSI) was developed using salinity data. The CSI uses a computational approach similar to the Standardized Precipitation Index (SPI). The CSI is computed for unique time intervals (for example 1-, 6-, 12-, and 24-month) that can characterize the onset and recovery of short- and long-term drought. Evaluation of the CSI indicates that the index can be used for different estuary types (for example: brackish, oligohaline, or mesohaline), for regional comparison between estuaries, and as an index of wet conditions (high freshwater inflow) in addition to drought (saline) conditions. The following three activities, completed in 2019, enhance the use and application of the CSI and will be presented:

A software package was developed for the consistent computation of the CSI that includes preprocessing of salinity data, filling missing data, computing the CSI, post-processing, and generating the supporting metadata.

The CSI has been computed at sites along the Gulf of Mexico (Texas to Florida) and the Southeastern Atlantic Ocean (Florida to North Carolina); and

Using telemetered salinity data, the real-time computation of the CSI has been prototyped and disseminated on the web.

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A systems approach to nitrogen remediation in a coastal watershed

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The EPA's Office of Research and Development (ORD) and its local partners are using a systems approach to deal with pervasive groundwater nitrate contamination on Cape Cod, Massachusetts. Here a sole source aquifer, loaded with nitrogen for decades, discharges to ponds, rivers and estuaries, many of which now have Total Maximum Daily Loads (TMDLs). To meet TMDL goals, towns across the Cape are pursuing traditional technologies (i.e., gray infrastructure) alongside alternatives, in coordination with a large network of public and private partners. Representatives of these groups recently participated in a problem formulation workshop, convened by ORD and the Barnstable Clean Water Coalition (BCWC), to identify current outstanding research questions and knowledge gaps impeding progress. Progress is fundamentally constrained by the existence of thousands of non-point sources, long groundwater travel times, cost and implementation of expensive solutions, issues that are further compounded by lack information on the performance and social acceptance of alternative technologies. ORD and BCWC built upon this workshop and other meetings to engage in research to inform the use of nitrogen-mitigating interventions including restoration of cranberry bogs and other wetlands, deployment of innovative/alternative (IA) septic systems and aquaculture in a target watershed. Studies of these interventions concurrently consider nitrogen attenuation along with cost and broader impacts on people and the environment. Research plans are developed using a translational science model responsive to stakeholder needs and changing local conditions. The systems approach taken by ORD refers to multiple aspects of the research design which 1) examines connected environments across the recharge-discharge continuum of a watershed, 2) explicitly integrates social and biophysical perspectives 3) actively engages stakeholders, throughout the process, in the target and similar watersheds. This presentation explicates the mechanics, and shares some early findings, of this solutions driven research for groundwater nitrogen remediation in coastal settings.

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Water Prediction Tools for Informing Climate Adaption Strategies as a Focus of Community Engagement

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Evaluating the effectiveness of adaption strategies aimed at mitigating the negative consequences of anticipated climate change requires modeling approaches that are (1) functionally and structurally accurate, and (2) appropriately sensitive to changes in forcings, land use, and land cover over a range of potential future scenarios. Models of this type will most certainly rely heavily on physical process representations in a high performance computational (HPC) environment that allows explicit representation of multi-dimensional heterogeneity. That is to say, to investigate climate change impacts and test mitigation and adaption strategies, the complexity of nature demands the use of models that can describe the characteristics of large watersheds. In essence, these models should emphasize "getting the right answer for the right reason" using excellent coupled physics rather than parameter tuning of simplistic models that do not include change-appropriate descriptive parameters or exhibit realistic sensitivities to variation in forcing inputs. This presentation discusses recent efforts aimed at the development of such models. Rather than emphasize proprietary or "named" models, the author proposes creation of a suite of tools in an HPC environment that facilitates process-level testing and validation of coupled physics-based hydrological representations. Two examples are shown that provide a potential roadmap for engaging the research and water management communities in a productive collaboration aimed at lowering the bar for the application of supercomputers for evaluating climate change mitigation strategies in a way that fosters community involvement and applies scientific evaluation to advance "best-in-breed" modeling technologies. The proposed approach encourages evidence-based model selection for simulating diverse watersheds, and a community framework for improved process-level understanding through simulation.

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Science Needs of Arizona's Watersheds

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Watersheds are a natural unit of land management, especially in water limited environments like the West. However, a key constraint on improved management is the patchwork of ownership and interests in land and water management. As typically no single organization or agency owns or controls the land across watersheds, collaboration is needed to achieve ecosystem or landscape scale goals like planning for fire, providing habitat for wildlife, combating invasive species, and managing for water quality or to reduce risk of downstream flooding. Local, state, and federal institutions, as well as tribes, support watershed work in cooperation with individual landowners and groups. As new watershed groups are created to help growing populations deal with increasingly scarce water supplies, there is a growing impetus to apply previously learned lessons.

To support the systematic identification, sharing and application of those lessons in Arizona, the Cross Watershed Network interviewed watershed practitioners in eight state or regional watershed councils across the country, as well as ten organizations that support watershed planning and the leaders of twenty watershed management groups across Arizona. Although each watershed group is unique, many face common stressors and expressed a need for support to communicate, build capacity, collect and manage data to prioritize restoration efforts, collaborate more effectively, develop political support, and fundraise. A standard science need across Arizona is to identify management actions that address priority problems and assess the expected impacts and costs of improved management systems. Another common need is for geospatial support to identify problem areas across jurisdictions, and to consistently integrate relevant information from land management agencies, particularly the Bureau of the Land Management and Forest Service. A core group of watershed partners, through the Arizona Cross Watershed Network, is planning the first statewide summit of watershed groups to share best practices, identify priority research and management needs, and establish a sustainable mechanism for cross watershed collaboration and greater collective progress on watershed health across the state. This project will also share knowledge about Arizona statewide support for watershed planning and collaboration with similar programs in Idaho, New Mexico, Colorado, Utah, Wyoming and Montana.

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Watershed Functional Zone; Multi-type multi-scale integration for understanding watershed functioning

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Predictive understanding of watershed function and dynamics is often hindered by the heterogeneous and multiscale fabric of watersheds. Recent advances in remote sensing has revolutionized the way we characterize watersheds from bedrock to canopy such as LiDAR and multispectral/hyperspectral technologies for high-resolution topography/geomorphology, and plant species/structure. In addition, airborne electromagnetic surveys provide subsurface structure and properties across watersheds that were previously characterized only through borehole data. However, there is still a challenge to integrate all these datasets for understanding watershed organization and for estimating and predicting integrated watershed functions such as ecosystem responses to climatic perturbations and nutrient exports.

This study explores a variety of machine learning techniques — unsupervised learning such as hierarchical clustering and autoencorders as well as supervised learning such as random forest — to gain quantitative understanding of watershed organization and functions. We hypothesize that (1) the co-evolution of watershed terrestrial systems creates co-variability among subsurface/surface spatial features (such as topographic, plant, snow and geological metrics), (2) we can reduce the parameter dimensionality by exploiting such co-variability, and (3) we can identify several representative landscapes — watershed functional zones — that capture distinct characteristics of those co-varied properties and associated watershed functions. We demonstrate our approach using airborne electromagnetic survey, LiDAR, snow survey, hyperspectral data collected over the East River Watershed (near Crested Butte, CO, USA). Results show that unsupervised learning is powerful to identify the surface/subsurface co-variability such as bedrock fracturing and plant species over the watershed, and identify several key zones that capture watershed-scale heterogeneity. Supervised clustering results shows that the elevation, aspect and geology are the key controls on both drought sensitivity and nitrogen export, and that we can map watershed "functioning" zonation, and predict nitrogen export in unmeasured sub-catchments based on spatial features and annual peak SWE.

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Integrated network design for a next-generation water observing system in the Delaware River Basin

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Abstract—Advances in technology have accelerated efforts to improve baseline environmental monitoring in the United States. Enhanced baseline data, coupled with predictive models, will greatly improve our capacity for early warning of hazards and early detection of trends. The U.S. Geological Survey is developing an Integrated Water Science initiative that includes a “Next-Generation Water Observing System" (NGWOS) designed to provide high-fidelity, real-time data to inform modeling and assessments of water quantity and quality. The implementation of NGWOS in the Delaware River Basin is applying innovative strategies for network design to cost-effectively track hydrologic, ecological, and socioeconomic dynamics across the river basin. Monitoring is implemented at locations representing the range of physical, chemical, biological, and socioeconomic conditions. This novel, multi-scale, interdisciplinary approach to observing network design could enable cost-effective data integration among multiple existing networks nationally and internationally, with the goal of detecting, understanding, and addressing changes in complex socioecological systems.

INTRODUCTION

Environmental monitoring is a critical service for sustaining the health and well-being of a modern society. Resource managers and health and safety officials depend on accurate hazard and resource disturbance forecasts, that are in turn dependent on scientific understanding of complex natural systems and reliable monitoring data for anticipating change. Resource managers must anticipate all disturbance factors, both natural and anthropogenic, and need to know how those disturbances interact to buffer or exacerbate the overall stress on the resources in question. Models for explaining and predicting natural and human-made systems need a full range of baseline conditions, disturbances, and response characteristics represented within the available monitoring

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data. Model inaccuracy and uncertainty are usually due to the lack of such monitoring data. Uncertainty cannot be understood without monitoring data to verify our assumptions and research to understand detected patterns.

The complex, hierarchical need for research and monitoring exposes a further conundrum in science-based decision making. It is not possible or affordable to anticipate the need for detailed, long-term data, or to assess the complex changes, interactions, and feedbacks caused by disturbances at every specific location where resource managers might need information (Murdoch and others 2014). “Representative” sites are often used as a means of extrapolating information. However, selecting a few locations as representative without clarity about their regional context, i.e., what they represent and when they are representative, is also too vague for effective decision support. Models can expand our understanding beyond individual research sites to other locations or regions of interest, but monitoring data are needed to verify models and define their uncertainty. Next-generation monitoring will apply advances in technology, but without a cost-effective network design that integrates research, modeling, and long-term observing over the full range of system responses to natural and man-made disturbance, that new technology alone is unlikely to improve decision making anytime soon. The U.S. Geological Survey (USGS) is developing an Integrated Water Science initiative that includes a “Next-Generation Water Observing System" (NGWOS) designed to provide high-fidelity, real-time data to inform modeling and assessments of water quantity and quality (USGS 2020). This manuscript describes a process being applied in the Delaware River Basin (DRB) for designing a cost-effective, multi-scale, and interdisciplinary information network to deliver the science needed for resource management and policy decisions.

THE NETWORK CHALLENGE

The charge given to the DRB network design committee was to meet the following operational challenges:

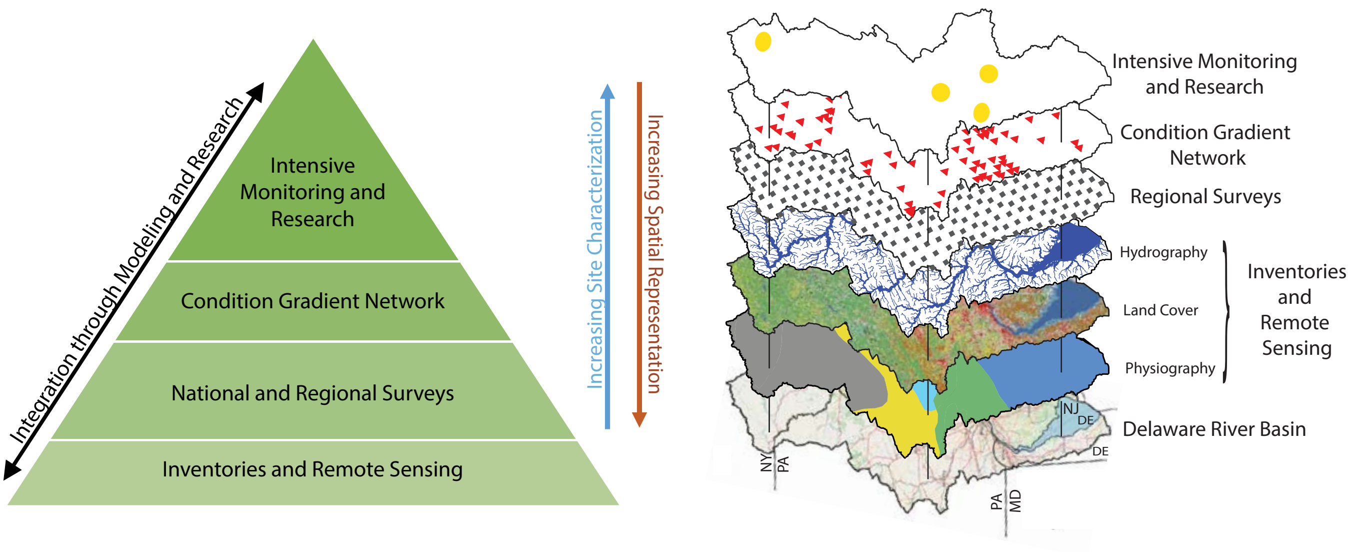
- Describe the spatial and temporal dynamics of the DRB as a complex system, including all factors (environmental and socioeconomic) that can influence water resource conditions and responses to management decisions.
- Fill the dual need of long-term prediction for planning and adaptation, and rapid detection for hazard identification and initial response.
- Leverage existing capabilities to expedite trend detection and minimize cost.
- Incorporate “test beds” for investigating new technology to optimize monitoring accuracy and efficiency.
- Optimize the transfer value of science information from where we measure and understand environmental issues to where that understanding will support science-based management and policy decisions.

The complexity of the design challenge implied that resulting data must support a variety of modeling and assessment needs, at a range of temporal and spatial scales, incorporating a range of science disciplines, at an affordable price. Establishing long-term measurement of core indicators of environmental change or disturbance has often met with resistance (Lovett and others 2007). Challenges have included the cost of collecting data, the concern that expanded monitoring will steal funding needed for research, uncertainty of what kinds of data will be needed to address future issues, and the limited transfer capability from measurement plots to unmeasured locations where decisions are being made. Few science programs have considered how strategic integration of research and monitoring could cost-effectively address many of those challenges by using (a) measurement methods appropriate to specific spatial and temporal conditions and (b) modeling to bridge those scales of measurement. The DRB pilot of the NGWOS is an effort to address these and other concerns by leveraging existing networks, adding new monitoring to fill information gaps, and nesting scale-appropriate measurements at the plot, stream-reach, watershed, regional, and global scales so that models can be built and verified to extrapolate information from measurement points to management focal areas.

THE MULTI-SCALE DESIGN

A multi-scale monitoring design establishes transfer value, defined as the ability to extrapolate information across scales of space (e.g., from a study area to other similar locations, or to the broader landscape) and time (e.g., from intensively measured episodic events to periodic measurements across decades). The multi-scale network design applied in the DRB by the NGWOS pilot is based on the Framework for Environmental Monitoring and Research (FEMR) published by the White House Committee on Environmental and Natural Resources (Bricker and Ruggiero 1998, NSTC 1997), and modified by the USGS (Murdoch and others 2014). The Framework starts with the necessary assumptions that (a) the processes controlling ecosystem function are generally consistent across similar landscapes and (b) by contrast, ecosystem condition is highly variable from place to place (e.g., diurnal water temperature, chemical concentrations, or water use and release). The variability in condition can be mapped to generate a spatially and temporally expansive database of ecosystem vulnerability, which through modeling can be used to transfer knowledge gained at research sites to the broader landscape. If there are differences in the controlling processes, research on each process is needed, and monitoring must be put in place to determine where each process controls ecosystem function across the landscape.

The FEMR network design describes four tiers of data collection. The triangular depiction of the Framework in figure 1 reflects a balance of monitoring intensity among tiers, where the greatest intensity of monitoring is at few research locations and greater extent of monitoring is achieved in surveys and remote sensing (Bricker and Ruggiero 1998; fig. 1). An additional tier of "condition-gradient" monitoring stations was added to the Framework to ensure representation of the range of possible ecosystem or disturbance conditions encountered in the target region such as the DRB. Such a characterization is an apt description of many stream gaging and stream-quality networks. Selected indicators of change are measured at condition-gradient sites at a frequency adequate for depicting their spatial and temporal dynamics—such as streamflow gages with chemical and/or biological monitoring. This "Condition Gradient" tier of measurement allows us to shift "representativeness" from the individual sites to the population of monitoring stations, thus ensuring that the data collected describe the full



Modified from Bricker and others, 1998; Murdoch and others 2014; Environmental Monitoring Team, Committee on Environment and Natural Resources, National Science and Technology Council, 1997

Figure 1—Multi-scale structure for an environmental monitoring framework with map diagram illustrating interdependency of intensive monitoring and research sites, condition-gradient networks, regional survey points, and wall-to-wall data coverage from inventories and remote sensing that, together, support comprehensive environmental tracking.

range of ecosystem dynamics and possible management challenges for sustaining water quality and availability (Murdoch and others 2014).

Surveys (statistical representation) and inventories or remote sensing (wall-to-wall coverage) of key indicators of ecosystem condition (status) can be used to derive a spatial coverage for translating science from the research and range-defining stations to the river basin (fig. 1). A cost-effective dataset for modeling whole-system vulnerability to disturbance can be established by nesting a small number of research stations within a network of less costly measurements using the condition gradient and survey stations, and the remote sensing coverages. This layered approach resolves the challenge of defining what each individual site represents while allowing for shifts in condition over space and time to be used in trends detection in both average and extreme conditions (Murdoch and others 2014).

PRACTICAL STEPS TO NETWORK DESIGN AND IMPLEMENTATION

The DRB network design is following a step-wise strategy to populate the data framework described above. Those steps are summarized as follows:

1. Prioritize with stakeholders the key management issues and decisions to be supported by the network.
2. Use the multi-scale framework to compile and organize existing data sources relative to those decision-support objectives.
3. Characterize data from step 2 using existing modeling capabilities to determine gaps in data and understanding for describing the full range of factors controlling ecosystem function. In the case of the DRB NGWOS pilot, we took the following approach:
   a. Use existing data and models to note correlations among existing

monitoring stations and gaps in spatial representation of environmental conditions.

b. Use available data to compute cumulative frequency distributions (CFDs) representing the range of observed watershed and river characteristics pertinent to the issues being addressed (e.g., range of water chemistry concentrations, water use, watershed impervious surface).

c. Superimpose existing monitoring stations onto the modeled CFD curves to visualize gaps in data collection that, if filled, would decrease uncertainty in models of basin-wide status and trends.

d. Identify potential new monitoring stations that fill gaps in the distribution of existing stations.

4. Establish the new monitoring stations and calculate decreases in uncertainty in the models from the addition of new data.

The goal in implementing these steps is a monitoring network that measures changes in both controlling processes and indicator conditions across the basin.

IMPLEMENTATION OF THE DELAWARE RIVER BASIN NGWOS DESIGN

Application of these network design steps in the DRB began in the spring of 2018, after selection of new gaging stations for the NGWOS pilot was already underway. Funding and planning time constraints on the design options were therefore uniquely limited relative to future implementation of NGWOS in other river basins. However, all steps of the process described above were implemented or are now in process to some degree.

Establishing the Key Issues Driving the Network Design

Stakeholder workshops hosted by NGWOS and prior stakeholder engagement by staff at the USGS Water Science Centers in the DRB were used to develop an initial list of issues as the basis of the network design:

- Anticipation and management of floods and droughts
- Balancing the requirements of eco-flows in the river with water availability for human use
- Managing for specific conductance and water temperature (salt front and fish habitat)
- Maintaining or improving water quality (groundwater and surface water)

Using this list, the network design team selected a set of core stressor and ecosystem function response parameters that could inform models of sustainability (table 1). The list of indicator variables was used in the CDFs for defining existing network capabilities and gaps. As with many river basins, issues in the DRB ranged from basin-wide concerns to important focused topics. One such critical issue is balancing management of diversions from three headwaters reservoirs for New York City, while releasing enough water to support flow and temperature requirements in downstream waters.

Characterization of Existing Data

Existing models and data from multiple streamgages in the DRB were available for assessing data gaps relative to the NGWOS focal issues. These models describe flow, water use, and water quality characteristics at existing USGS monitoring stations and

Table 1—Core stress and response parameters used to address stakeholder-determined issues in monitoring network design

Physical and chemical characteristics	Land cover and land use	Water use	Regional model predictions
Watershed size	Agriculture	Groundwater withdrawals	Nitrogen flux (SPARROW)
Slope	Urban development	Surface water withdrawals	Phosphorus flux (SPARROW)
Sinuosity	Wetland	Domestic self-supplied population	Suspended sediment flux (SPARROW)
Reservoir density	Forest	Irrigation	Gage correlations
Flow and water quality	Stream canopy	Point source discharges	
Percent watershed underlain by carbonate material	Impervious area		
Base flow index	Road density		
Wetness index	Population		
	Drain tiles		
	Road crossings		

revealed gaps in the scale and spatial representation of watershed features. Three different models were used to assess (a) flow correlations at gaged reaches across the basin, (b) indicators of how well an active gaging station represents streamflow in upstream reaches, (c) the relative effects of land use in stream reaches across the DRB, and (d) a comparison of statistical and process models for determining uncertainty in correlations for flow and water availability. Results from these 4 model analyses are briefly described here:

Streamgage correlation—This model utilized flow statistics at existing and discontinued streamgages to map correlations among stations in the timing and magnitude of flow dynamics (fig. 2).[1] Flow correlations were strong among gages in the northern half of the DRB, and weak among gages in the coastal plain. These data suggest taking special care to document the full range of flow regimes when designing the condition gradient network in the southern half of the basin.

Upstream reach correlation—This model assessed how well the flow conditions at any stream reach are represented by a streamgage with shared drainage area. Two ratios are calculated for each National Hydrography Dataset (NHD) reach, a ratio of the closest upstream gaged drainage area to the reach drainage area and a ratio of the reach drainage area to that of the closest downstream gage. The larger of these two ratios indicates how well the gaging network

[1] Written communication. 2018. Terence Messinger, Physical Scientist, U.S. Geological Survey, Charleston, WVA, 25301.

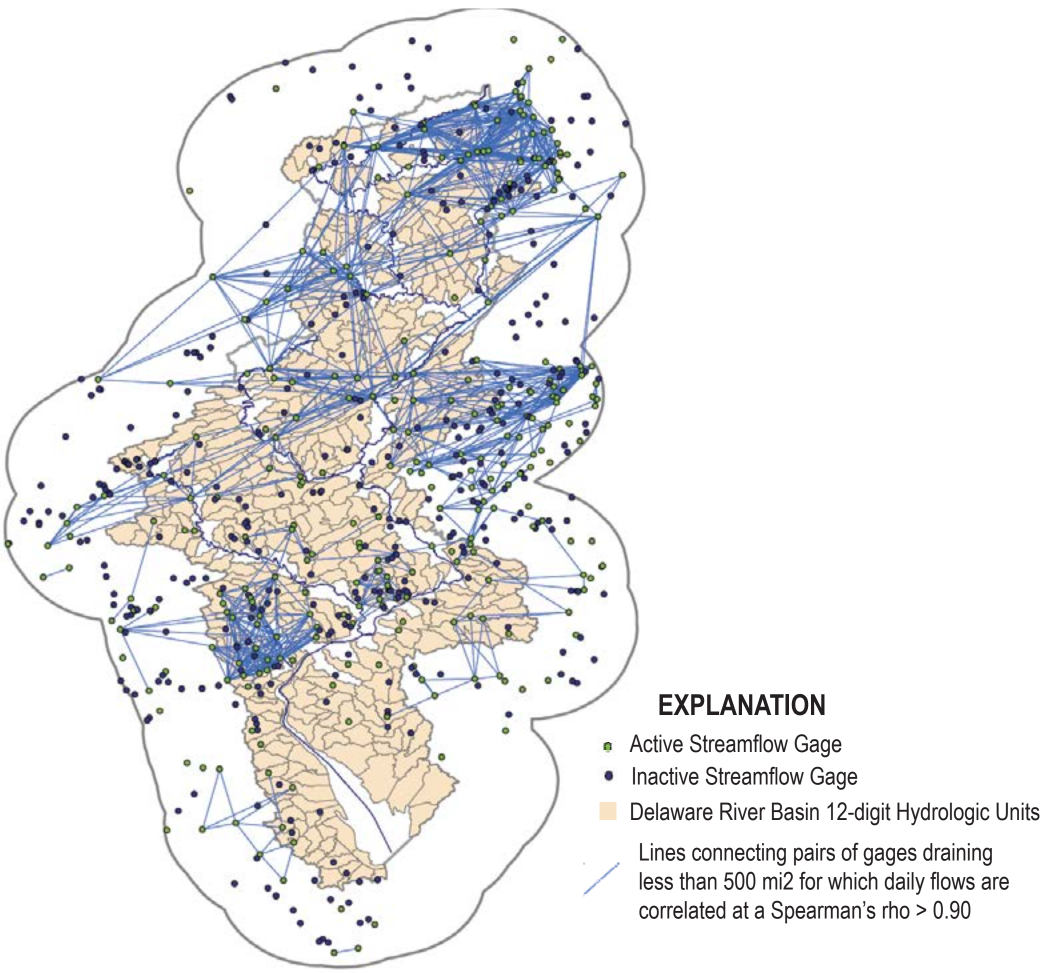


Figure 2—Map showing correlation analysis of U.S. Geological Survey streamflow gages active in the Delaware River Basin, water years 2008–2017. (Written communication. 2018. Terence Messinger, Physical Scientist, U.S. Geological Survey, Charleston, WVA, 25301)

represents streamflow in that reach (Konrad and Voss 2012; fig. 3). The results indicate that small streams are underrepresented by the existing streamgage network and identify areas of comparably sparse streamgage coverage.

Relative land use effects assessment— Tri-linear plots were used to rapidly assess the coverage of monitoring sites relative to the percentage of agricultural, urban/suburban, and forested land use in the watersheds draining stream reaches in the DRB (fig. 4). Land use data accumulated for each reach in the NHD were readily available to support this analysis (Wieczorek and others 2018). Forests and wetlands were grouped together as representative of land use settings with less human impact. The analysis revealed an overweighting of forested and mixed-use watersheds in the existing monitoring network, poor representation of agricultural end members, and a sparse representation of urban end members (>75 percent agriculture or urban use, respectively).

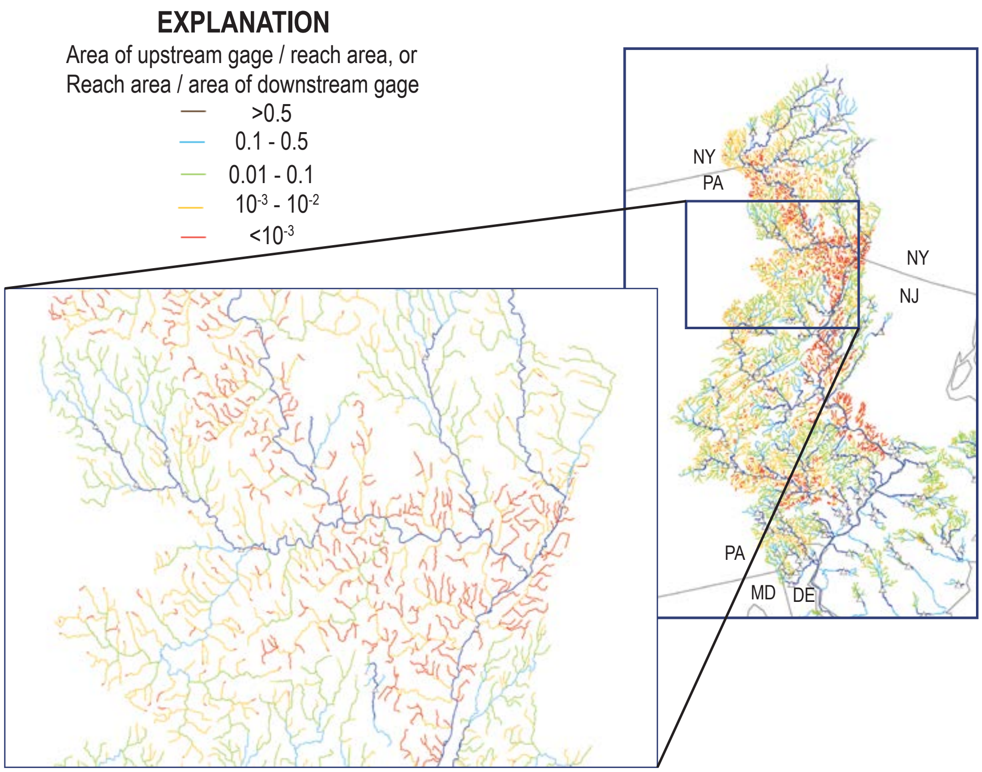


Figure 3—Map showing differences in density of streamflow gage coverage in the Delaware River Basin based on National Hydrography Dataset reach area relative to watershed area of the nearest upstream or downstream streamflow gage (Konrad and Voss, 2012).

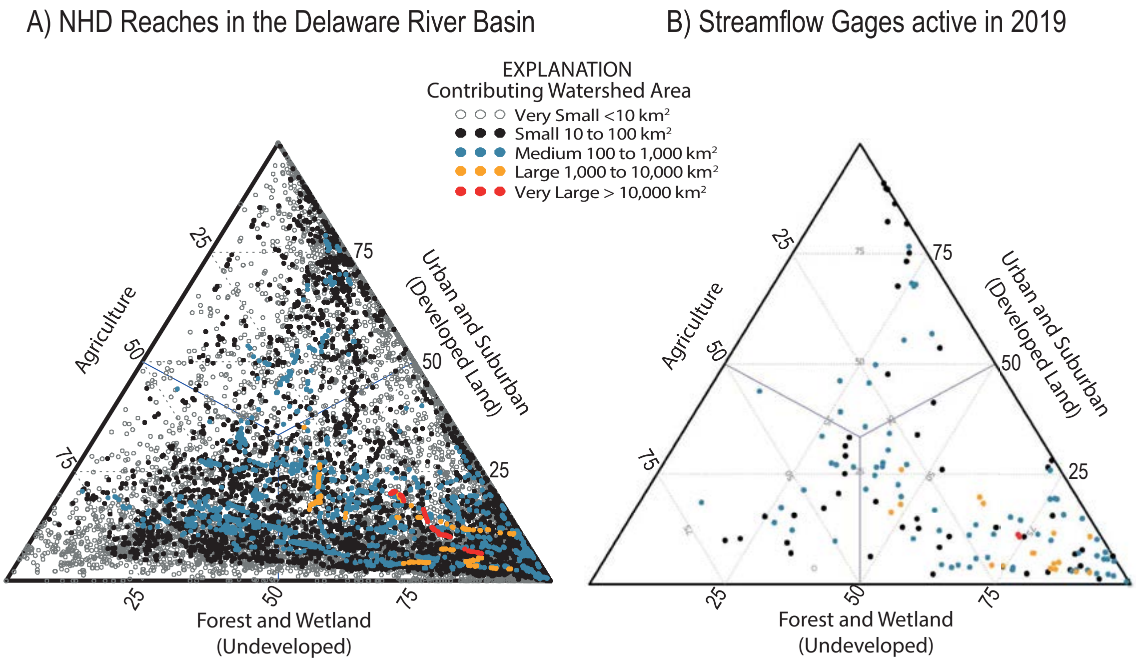


Figure 4—Trilinear diagrams showing relative proportions of major land cover categories (Dewitz 2019) and watershed area in the Delaware River Basin for A) 16,000 National Hydrography Dataset stream reaches and B) active streamflow gaging stations in 2019.

Uncertainty of flow and water quantity simulations—This assessment compared a statistical and a process-based model for determining uncertainty in flow correlations with selected physiographic variables (Stuckey 2016, Williamson and others 2015). Results of the model comparison yielded the following:

- Simulation of streamflow and water availability for very small basins (< 50 km^2) is dependent on localized information on storm intensity and duration, daily water use, and surface water-groundwater interactions, the precision of which becomes less important as basin size increases. This suggests that the level of detail in regional/national databases is not adequate to inform models of these small basins.
- Subwatersheds in carbonate regions are difficult to simulate because much of the water use in these basins accesses groundwater that is not recharged on the time step used by the models. These results likely reflect the combined effect of carbonate rock and relatively high development that accesses this groundwater and returns it to the stream as wastewater.
- Of those basins in heavily populated areas, only a few could be simulated by each of the models, and those simulations were poor, suggesting that differences in local water use, not land use, were the reason for poor flow simulations.

Analysis of the combined results of these modeling efforts in the DRB indicated the following characterizations of the existing monitoring network:

- Streamflow and water quality per unit area of watershed vary across the basin, but similarities exist among stream and river reaches within the five major physiographic provinces. Monitoring across the range of conditions within each province was therefore recommended.
- Flow simulation and correlations appear weakest in areas of high water use in the carbonate and coastal plain provinces. Additional monitoring in these areas should therefore reduce uncertainty for concentration-discharge relationships.
- Existing monitoring in the mid- and southern river basin does not include small tributary basins that best represent the range of conditions.
- A low density of gages on small tributaries to the Upper Delaware Scenic and Recreational River could be causing higher uncertainty in flow modeling for that subbasin (Williamson and others 2015).

These recommendations were used to focus additions to the river monitoring network in the next phase of implementation.

Defining Data Gaps Using Cumulative Frequency Distributions (CFDs)

It is important to assure that network expansion improves regional context by adding data collection in locations and settings that are currently unrepresented. This step in the design process ensures that the range of flow and water quality conditions, and land and water stressors are represented in the network. The CFD curves depict the cumulative frequency of the available reaches (in percent) versus a measured watershed characteristic. The CFD curves for the DRB were generated using a combination of existing data from NHDplus (Wieczorek and others 2018) and SPARROW modeling (Ator 2019), so that a population of approximately 16,000 streamflow reaches was represented in the CFDs. The cumulative frequency of reaches for the range of watershed areas within each physiographic province was plotted against watershed area, and the existing streamgages were superimposed on these curves based on their contributing area (fig. 5). The graphs show that the existing network is biased toward larger basins as stations fill the upper 50 percent of drainage areas but is sparse for smaller drainage areas (< 10 square miles). The CFDs can be used similarly to identify settings or conditions that have comparably dense coverage, indicating opportunities for optimization and realignment of monitoring resources.

The CFDs for describing physical and water quality conditions across the basin were created for 25 variables in each of the 5 physiographic provinces (table 1). Measurement of some water quality variables, such as temperature, had continuous recording sensors in numerous existing gages, and roughly represented the range of temperature conditions in each province; routine collections of water samples for laboratory analysis at existing stations were much less numerous, so adding water quality sampling to existing or new streamgages to represent low, medium, and high average concentrations of key constituents was recommended

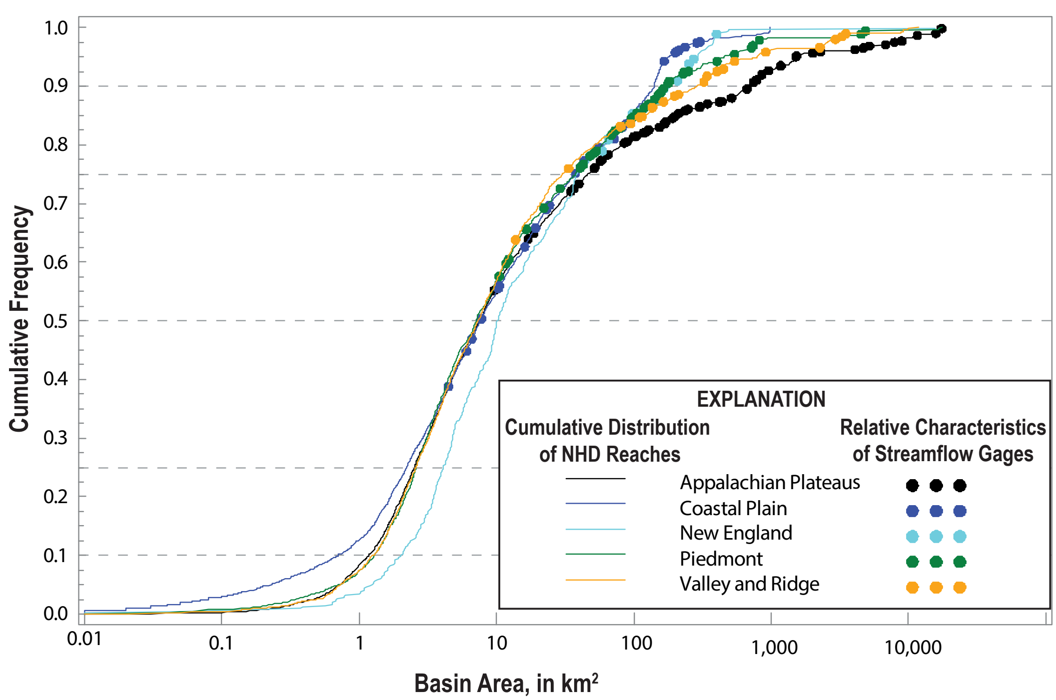


Figure 5—Diagram showing the cumulative distribution of contributing watershed area for NHD reaches in the Delaware River Basin grouped by physiographic province of reach location. Active streamflow gages are superimposed based on their contributing area and province to identify strengths and weaknesses in current monitoring.

(fig. 6). The USGS Water Science Centers in the basin had previously compiled lists of potential new monitoring stations based on stakeholder priorities, so water quality conditions for each of those potential gages were also plotted on the CFDs. Proposed sites that filled major gaps in the existing gage coverage of each curve were given highest priority for installation to complete the condition gradient monitoring of the framework.

Establishing Regional Survey Monitoring

Regional surveys provide a statistical baseline for translating scientific characterizations of landscapes from the research stations to other similar lands and waters in the study region (the river basin, ecoregion, county, etc.). The USGS Midwest Stream Quality Assessment (Van Metre and others 2018) provides an example of regional surveys that bridge the gap between intensive monitoring locations and basin-wide characterizations. Statistics like average concentrations and watershed yield, standard deviations of the population of places measured, and inflection points in the CFD curves representing shifts in concentration are all valuable for placing the research stations in a regional context, determining where else research results might apply, and verifying modeled projection of information across space or time. Design of each survey requires careful consideration of what factors control how measurements vary across the basin, to sample similar conditions at all survey points for comparison. A survey of water temperature, for example, should consider diurnal variability, shade from vegetation, time of the year being measured, etc. Effective measurement protocols for one parameter may differ from another.

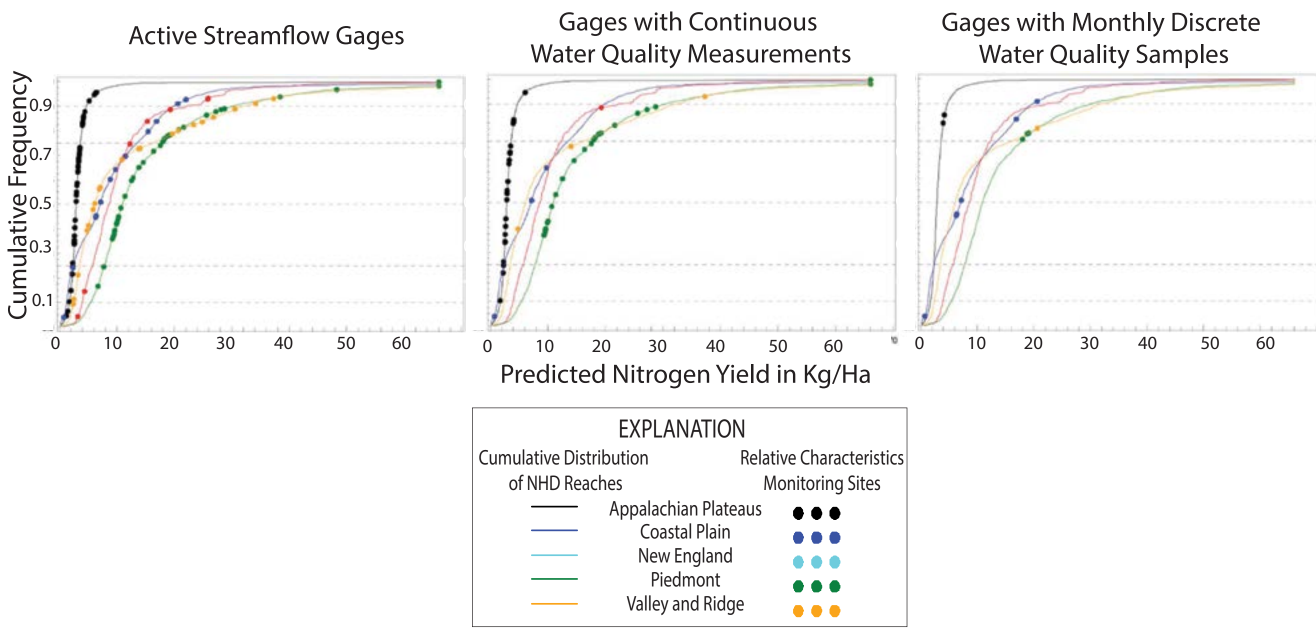


Figure 6—Cumulative distribution graphics for predicted nitrogen yield (Ator 2019) at National Hydrography Dataset reaches in the Delaware River Basin, grouped by physiographic province. Superimposed sites show characteristics of available monitoring locations for streamflow, continuous water quality, and discrete sampling sites with monthly samples collected at active gages.

Establishing Remote Sensing and Inventories

As with regional surveys, remote sensing and inventories need to be designed for requirements specific to each measurement being made and each management decision being addressed. Temporal constraints (time of day, season), landscape physiography (mountains versus broad valleys), and the human footprint (urbanization or agriculture versus forested landscapes) will all influence the comparability of measurements across the basin in specific ways for specific core parameters. Because inventories and remote sensing allow us to map the physical and chemical conditions across the river basin, they provide the spatial details for modeling process understanding from the research stations into the broader landscape. Geospatial database development for remote sensing of land use, topography, vegetation, and temperature are underway in the DRB. Advances in remote sensing technology promise to greatly expand environmental modeling and assessment (Schmugge and others 2002).

USE OF THE NETWORK FOR DECISION SUPPORT

As designed, the NGWOS network in the DRB should provide critical science information for multiple decision issues and locations in the basin. First and foremost, the efforts to broaden representation of streamflow and water-quality measurements through a fully represented condition-gradient network will ensure that models and assessments based on these networks more accurately support their intended purposes. Here are a few examples of the services the network can provide.

Establishing “Representative” Baseline Conditions for Measuring Trends

Determining what a specific research site represents of the broader landscape surrounding it has been a goal for many research watersheds. This goal is also a challenge as all landscapes have unique attributes that are not entirely replicated in other locations. Average (and thus most stable) conditions at a site representing a type of ecosystem are also typically insensitive as sentinels for detecting disturbance. Watersheds that represent average conditions will therefore be slow to reveal change compared to watersheds near some ecotonal boundary (e.g., low-buffered streams will exhibit episodic acidification from acid deposition sooner than well-buffered streams). A solution to this need for representation of the broader river basin is to periodically measure vulnerability indicators at multiple locations that represent the full range of conditions in the condition gradient network, and to map indicators of vulnerability to specific stressors across the entire resource using surveys, remote sensing, and models. Stations where we have detailed information can then be mapped into that context and the position of those stations within the CFDs will define what portion of the system they represent. Likewise, measuring at research stations as part of periodic regional surveys will place each survey in a temporal context. This more detailed representation of current conditions will in turn allow earlier detection of changes in ecosystem condition and function.

Measuring Trends Using CFDs

Shifts in the shape of CFD curves based on regional surveys can provide an indication of how ecosystems are changing over time across the DRB and provide a spatially integrated assessment that is difficult to achieve at independent fixed locations. Responses to basin-wide disturbance events (e.g., seasonality, climate change, regional shifts in land use, non-point source pollution) will differ from place to place. For example, hydrologic changes from April to July 2006 caused a shift in the shape of CFD curves of nitrate concentrations in tributary streams of the Upper Delaware Scenic and Recreational River (fig. 7; Siemion and Murdoch 2010). This ability to detect trends in the shape of the CFD curves for a range of stations provides more useful information on vulnerability than trends at one or two representative watersheds.

Assessing Vulnerability Thresholds and Mitigation Actions

Vulnerability of water resources to disturbance is generally a product of (a) the baseline ecological and socioeconomic condition relative to a threshold of stress beyond which a change in ecological functionality occurs, (b) the ambient or anticipated stressors on that condition, and (c) resilience of the combined socioecological system to resist change or recover if thresholds of disturbance are breached. With the network design, thresholds of stress beyond which a change of state for an ecosystem can occur can be studied at the research and condition gradient stations; maps of vulnerability indicators across the basin can then be drawn from remote sensing data and verified through measurements collected at the survey stations. Models of ecosystem response to

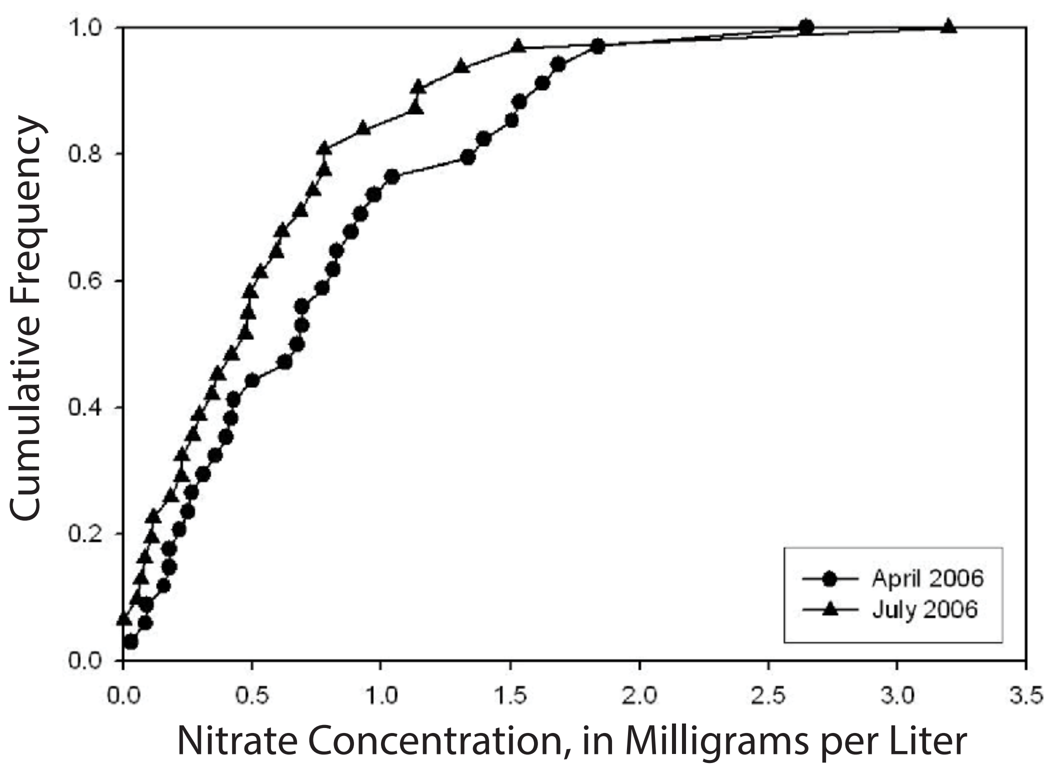


Figure 7—Cumulative frequency curves of nitrate concentration at condition gradient stream monitoring stations in the Upper Delaware Scenic and Recreational River from April high flow and July moderate-high flow in 2006.

stressors, and trends in ecosystem condition over time, can be used to predict when different parts of the DRB will approach vulnerability thresholds and what mitigation or adaptation actions might sustain a desired ecological (and socioeconomic) function beyond the stress event.

PUTTING IT ALL TOGETHER

No single component of the network design is sufficient alone to address the needs of decisionmakers in the DRB for scientific information, short of taking the time and funds to do a study of each issue in the locations where the decisions are being made. There are simply too many locations in need of information, and too little time before resource management decisions will be made whether science is available or not. A multi-scale nested monitoring strategy, in which technology test beds, small research watersheds, condition-gradient monitoring stations, surveys, remote sensing, and models are all components of an integrated design, and which leverages existing long-term data for early detection of trends, is the most cost-effective solution to meeting natural resource management needs for science-based decisions. The pilot of this network design in the DRB, which began in 2018, is providing a test case for development of more refined and cost-effective research, monitoring, and modeling networks by the USGS NGWOS program throughout the United States.

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From Forests to Faucets: A drinking water utility's approach to protecting its source through watershed management

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Central Arkansas Water

The Watershed Management Program (Program) is Central Arkansas Water's (CAW) source water protection program for its two water supply reservoirs, Lake Maumelle and Lake Winona. Combined, these watersheds cover 115,520 acres total and contain 16 square miles of reservoir-surface water, of which, CAW owns not only the reservoirs (over 10,000 surface acres), but also an additional 14,000 acres of property—all of which is managed by CAW and this Program.

Established from the Lake Maumelle Watershed Protection Plan, adopted in 2007, this program and has received national recognition as a leader in managing natural resources for the purpose of drinking water protection. When the Plan was finalized and adopted, the CAW Board established a clear vision for watershed protection where the utility and community would strive to "maintain [a] long-term, abundant supply of high quality drinking water for present needs and continuing growth of the community … and [provide] an equitable sharing of costs and benefits for protecting Lake Maumelle."

CAW staff strives to meet the challenges of this vision and implement its core values. The Program's goals are to protect, restore, and enhance the natural environment of the two watersheds through a variety of pollution prevention, watershed, and source water protection approaches as part of an overall strategy to maintain and enhance ecological and community sustainability. In the more than decade since the Plan's adoption, CAW has been hitting the task of watershed protection from all fronts. By expanding protection efforts from simple land acquisitions, to active forest and natural resource management practices, CAW is becoming a leader and model for watershed protection.

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Section 4: Watershed Response to Change

Changing Climate Variance: Implications for the United States Eastern Deciduous Forest

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Contemporary climate analyses rarely include equivalent attention to combined variance of hot (cold) and drought (extreme wetness) over time. This is of concern given little is known about how increasing (or decreasing) climate total variance may affect short and long-term ecosystem productivity. Investigations in the Eastern Deciduous Forest (EDF) biome stretching from the eastern (north-east West Virginia) to the midwestern United States (mid-Missouri) were undertaken to quantify rates and directions of climate variable changes. Analyses included long-term data sets (e.g. 1906—2016) from multiple locations using historic climatology, global change modeling, and other regional data sources. A cross-system EDF analysis during growing season months showed that mean net ecosystem exchange (NEE, µmol/m^2/s) was -5.76, -3.22 and -3.52 in 2009 during a period of extreme wetness, and -4.68, -2.18, and -0.09 respectively, in 2012 (extreme drought) at ecosystem flux sites in Harvard forest, Morgan Monroe forest, and central Missouri, respectively. This finding suggests that at the western edge of the EDF net ecosystem exchange (NEE) may be more adversely impacted (relative to east) by ongoing increased precipitation, precipitation variance and excessive wetness. In the eastern portion of the EDF, analyses showed an increasingly wet and temperate climate characterized by warming minimum temperatures, cooling maximum temperatures, and increased annual precipitation that have accelerated during the second half (1959 to 2016) of the period of record relative to the first half (1958–2016). Median air temperature and dew point values decreased with elevation at a rate of 5.2° C km^{-1} and 3.5° C km^{-1}, respectively consistent with decreasing vapor pressure deficits (-0.30 kPa km^{-1}). Results imply that excessive (persistent) wetness may become the primary ecosystem stressor associated with climate change in the distinct Appalachian region of the EDF. Ultimately, collective results indicate rapidly changing (spatially heterogeneous) climate variance throughout the EDF. This work therefore serves as an alert to the need for studies of potential impacts of total climate variance on forest and agricultural ecosystem health and productivity. This is important to ensure sustainability of ecosystem services, health, and productivity in a swiftly changing climate across the broader EDF region and similar temperate forest ecosystems globally.

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Combined effect of non stationary stressors in Choctawhatchee Watershed

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The hydrological processes and water balance in Upper Choctawhatchee River Watershed were modeled using the Soil and Water Assessment Tool (SWAT) from 1986 to 2015 to investigate the impacts of climate and land use change. Future daily rainfall and temperature, for next three decades, were simulated using CanRCM4 to provide SWAT model the climatic forcing to project stream flow. Projections were established under three different climate ensembles of different representative concentration pathways (RCPs) and one landuse scenario. The landuse scenario was built according to the current landuse change trend to reflect both management and unsupervised practices. Calibration and sensitivity analyses and bias correction were satisfactory. Model calibration metrics including p-factor, r-factor, NSE, and R^2 are 0.58, 0.53, 0.74, and 0.75 respectively. Results from simulated historic hydrologic processes reveals evapotranspiration (ET) as the most dominant pathways for water loss (ET/Precipitation=0.58). Surface runoff plays a major role in modulating the processes where 77% of the Total Flow is Baseflow. Projected climate impacts demonstrate higher temperature and seasonal change (longer periods between rainfall events) which reflects as strained water resources in projected stream flow. These changes, subsequently, influence the growth and crop and forest productivity in the region. Under the landuse scenario, ET decreases to 41% of the precipitation, and surface runoff drastically increases to 89% of the Total Flow and 60% of the precipitation. Surface water levels and infiltration rates significantly increase and decrease respectively which poses vulnerabilities to flood prone areas. Relying on rainfall for farming (irrigated row crops area makes less than 1.7% of the agricultural area) in combination with reduced agricultural landuse and increased urban area and population, will likely make the water use efficiency critical. The model has demonstrated satisfactory performance capturing the hydrologic parameters and can be used for further modelling of water quality (NPS and PS pollution) to determine the sustainable conservation practices.

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Long-term low flow responses to forest harvest treatments in the Pacific Northwest

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In the Pacific Northwest, seasonal low flows have important implications for aquatic species, drinking water supplies, and water quality. Regionally, long-term observations from experimental watersheds suggest summer flows are declining due to climate change and land management (Holden and others 2018, Kormos and others 2016, Luce and Holden 2009, Mote and others 2018). Results from multi-decadal studies suggest that historical timber harvest practices typically resulted in an initial period of increased summer streamflow followed by a gradual, but variable return to baseline flow, and later streamflow deficits (Coble and others 2020). These later deficits during forest regrowth are of particular concern in the region not only because of impacts to human use, but also because less water means aquatic species have both less habitat and less connectivity among habitats. Forest practices have evolved over the last several decades to better protect water quality, water quantity, flow regime, and stream ecosystems. To shed light on expected future conditions, a mechanistic understanding of harvest effects that incorporates the effects of climate variability is needed.

To understand the impacts of past and present forest management, we investigate how the water balance components are altered by harvest and regrowth over the 40- to 80-year time span. While the most immediate post-harvest effects (0 to 10 years) are well-documented, few studies document effects beyond the first decade. We describe and detail a successional stage-based theory that includes periods of 1) initial “green-up”, 2) early rapid regrowth, and 3) later regeneration and canopy closure (Brown and others 2005, Du and others 2016) We use three important catchment studies in Oregon, Idaho, and California to illustrate how hydrologic response periods manifest and vary with geography, precipitation regime, forest type, and harvest methods. All sites have managed mixed-conifer forests.

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Our wettest rain-dominated (transitional snow zone) sites are the H. J. Andrews (44.2° N -122.2° W) and Coyote Creek on the Southern Umpqua (43.22° N 122.70° W) Experimental Forests in the Oregon Cascades. Here, seasonal low flows increased the first decade post-harvest and then declined as much as 50 percent by year 25. Declines were observed through year 40 (Perry and Jones 2017).

Mica Creek, located in the Idaho panhandle (47.18° N -116.3° W), is a snow-dominated watershed where data from four nested watersheds were used to parameterize a Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta and others 1994) to simulate low flow response over a 40- and 80-year rotation. Simulations show August–September flow declines in the smallest catchments, but only when the entire 27 km^2 was harvested all at once did a substantial decline result. This is consistent with other results that do not detect low flow declines in large-scale catchment studies.

At the rain-dominated Caspar Creek Experimental Watersheds located in northern California's Coast Range (39.36° N -123.7° W), two 2nd-cycle logging experiments produced different low flow responses and recovery trends. The South Fork (SF) selection harvest (1971 to 1973) resulted in initial low flow enhancements during the first 5 post-harvest years (Keppeler and Ziemer 1990) while the North Fork (NF) partial clearcutting (1985 to 1986 and 1989 to 1991) resulted in a 12-year period of increase (Keppeler and others 2009). SF low flows returned to baseline levels and further diminished to deficit levels 8 to 21 years post-harvest (Reid 2012). On NF, post-harvest treatments (broadcast burning, herbicide application, and precommercial thinning) prolonged the period of low flow enhancements and deficits were not observed until 22 years after partial clearcutting (12 years after thinning) (fig. 1).

Factors contributing to the disparity of results across the region include forest type and stand condition, harvest method (silviculture, riparian and upslope harvest intensity, successional trends, etc.), but also weather patterns, climate trends, and other changes in vegetation. Investigations at the hillslope, plot, and tree scale are improving our understanding of how these factors affect the water balance and low flow regime at sites with differing physiography.

Ongoing research at the Caspar Creek Experimental Watersheds is designed in part to address knowledge gaps in our understanding of the processes that influence seasonal low flows. Collaborative studies investigate watershed responses across a range of forest stand density reduction treatments (20- to 75-percent reduction in basal area) implemented from 2017 to 2019. In addition to quantifying harvest effects on streamflow, experiments examine how harvest intensity influences the routing of water from hillslopes to streams, and how precipitation and fog inputs are partitioned among evapotranspiration, soil moisture, groundwater, and streamflow. Using historic measurements of water balance components, a Distributed Hydrology Soil Vegetation Model and River Basin Model (DHSVM-RBM) has been calibrated to analyze changes in stream temperature (Ridgeway 2019) and flow (Surfleet 2020). Such efforts are crucial to understanding how contemporary forest harvest practices may impact summer streamflow in future decades.

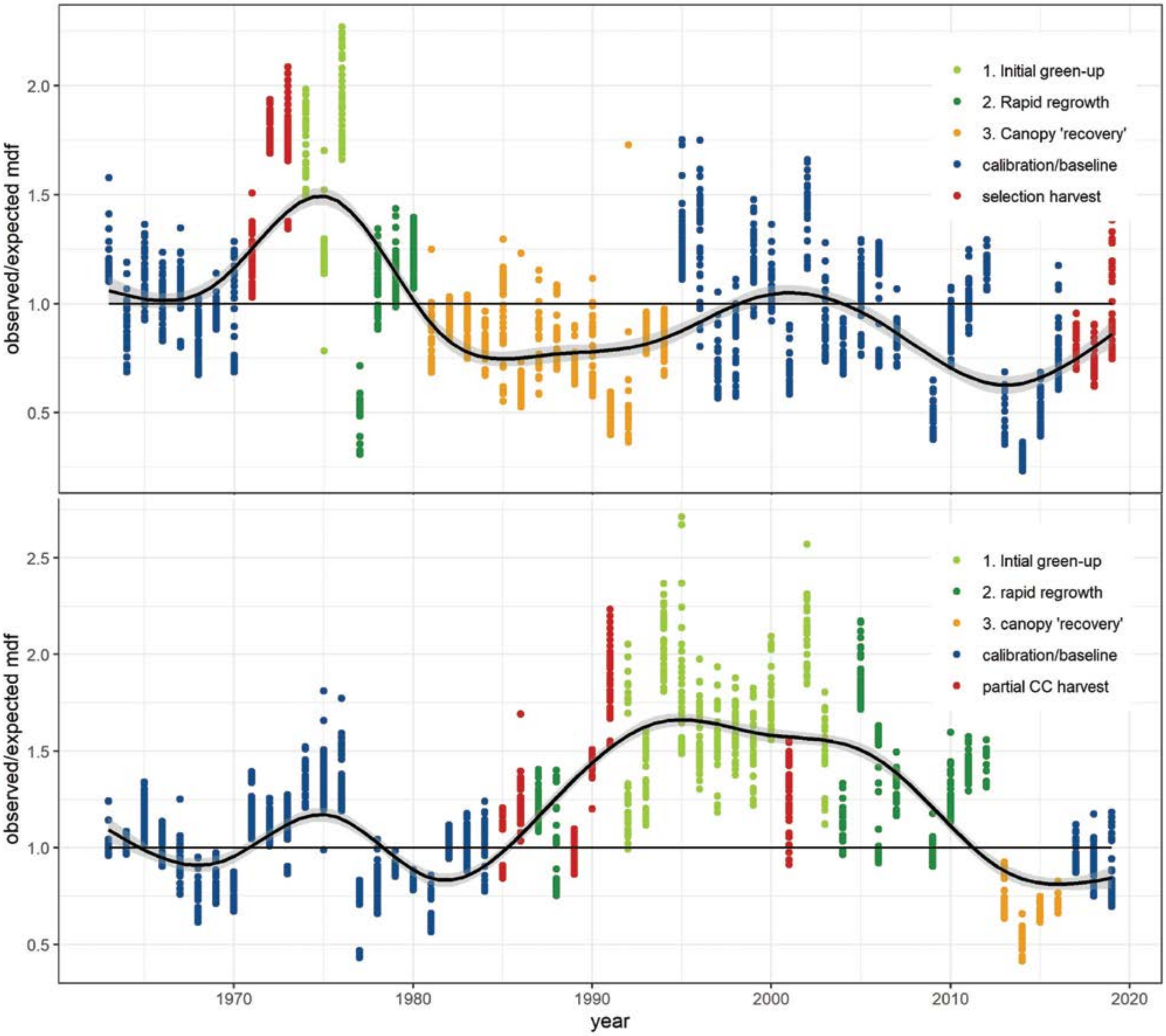

Figure 1—Ratio of observed to expected mean daily flow (mdf) for the lowest 10 percent of Caspar Creek flows by year for South Fork (top) and North Fork (bottom). Expected values are predicted from an Antecedent Precipitation Index with a recession coefficient of 0.985. Observations are color-coded by hydrologic response period: initial "green-up," early regeneration (rapid regrowth), and later regeneration (canopy "recovery") in bright green, dark green, and gold, respectively. Calibration period and harvest years are shown in blue and red, respectively.

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Field-based assessment of an urbanized montane headwater catchment: the impact of watershed-wide green stormwater infrastructure retrofits

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Robinson Design Engineers

Most stormwater research in the southeastern U.S. has occurred near the major academic research institutions located within the Piedmont. As a result, performance standards and design guidelines for green stormwater infrastructure (GSI) and other types of stormwater control measures (SCMs) do not readily transfer to the steep mountain environment, which is characterized by shallow soils, steep gradients, and intense rainfall. To provide insight into regionally-specific performance standards and design guidelines for GSI and SCMs, we established an experimental watershed in Asheville, NC.

We collected storm event measurements of creek stage, discharge, and sediment concentration within a first-order mountain stream draining approximately 100 acres of developed headwaters. These measurements were collected before and after the construction of six green stormwater infrastructure (GSI) retrofits upstream throughout the watershed. The experimental watershed is fully contained within the campus of Givens Estates, a retirement community of the United Methodist Church. The project is funded by the NC Clean Water Management Trust Fund, and the project is sponsored by RiverLink, an Asheville-based non-profit dedicated to promoting the environmental and economic vitality of the French Broad River and its watershed.

This presentation will provide an overview of the experimental watershed and project history, outline the goals of the grant-funded project, and present data from storm event measurements before and after implementation of GSI retrofits—which reduced pollutant sediment output by as much as 61 percent. The presentation will also describe the applicability of the research, and how the lessons learned through this project can benefit the design of GSI projects in the difficult montane landscapes of the Southern Appalachians.

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Lessons learned from stream restoration partnerships in North Carolina: a State forestry agency's perspective

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Since the mid-2000s, the North Carolina Forest Service has hosted and participated in multiple stream restorations on some of the more than 65,000 acres of land under its management. These projects were made possible through partnerships among landowners, agencies, academia, grantors, and the private sector. Based upon our experiences, we have identified some lessons learned for success.

Get buy-in from local stakeholders, internal and external—Motivation of internal stakeholders and supervisory acceptance are key first steps to building support within a land management agency. Stream restoration requires a long-term stewardship commitment. It should meld with other land management goals to achieve the best synergies and not be viewed as an outlier in the total package of resource objectives. Even when restoration is on public lands, the neighboring landowners are key to the project's overall acceptance within the community. If the restoration can be demonstrated with success on the public land, then other property owners can see the benefits of hosting such work upon their land. Fostering landowners' interest can spread the effectiveness of water resource restoration and protection within a watershed.

Strategize thoughtfully—Take a holistic approach before attempting a restoration. Assess the overall water resources on the tract, and prepare a plan with recommendations, options, and budgets. This allows prioritization of needs and opportunities while demonstrating thoughtful planning to prospective collaborators and funding partners.

Before and after the restoration, be patient—Stream restoration may take years of preparation while on-the-ground construction may take only a few weeks. Afterward, there is a commitment of multi-year monitoring and maintenance. It takes time for riparian vegetation to re-establish; for water temperatures to moderate; and for aquatic life to recolonize. In one of our projects, it was 15 years between the initial land acquisition to the point of introducing a trial population of native trout into the headwaters of the restored stream.

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Be creative and persistent in seeking funding—Funding stream restoration requires actively pursuing opportunities, engaging prospective funding partners early and often, and demonstrating a proven track-record of efficient and transparent project management. The first proposal may not be accepted; learn from that and continue to improve the likelihood of funding the project in the future. Internalizing some of the costs (i.e., matching funds) may be appropriate as another facet of an agency's ongoing resource management duties.

Balance the need for immediate local fixes with addressing watershed-scale impacts—One of the biggest challenges is where to prioritize resources. Should we 'fix' a relatively localized problem, or attempt to remedy a landscape-scale concern? Stream restoration has become an important tool for enhancing watershed resiliency, and this field of expertise continues to broaden in its application on local and watershed scales.

Cast a wide net of collaborators and enlist the experts—Stream restoration is multidisciplinary. Seek input from plant ecologists, foresters, aquatic biologists, hydrologists, engineers, and others. Collaborating with technical experts who are recognized as leaders in their field has proven successful in planning, design, engineering, and construction. Visit other projects as a reference before hiring. Seek counsel from multiple restoration professionals to identify the one who best understands your needs and aligns with your organization's mission and values.

Set realistic expectations—While restoration metrics such as linear feet or acres are important, those measures do not equate to a successfully restored and functioning, dynamic natural system. Expectations may include stabilization of physical stream characteristics or attaining a water quality parameter (i.e., temperature or dissolved oxygen). The overall objective of 'habitat improvement' is aspirational but should include tangible, intermediate goals.

Prepare for repairs, maintenance, and the unexpected—Stream restoration, much like forestry, is a classic example of adaptive management. A project manager must be adept at overcoming unexpected challenges while addressing variable concurrent factors. Washouts of restored streams are likely. Initial plantings may not survive. Increased in-stream sediment mobilization may occur. Come to an understanding upfront with the contractor and designer regarding how much responsibility each is willing to bear for restoration performance and warranty work.

Use what you've got and take advantage of good weather—Utilizing rocks, logs, or rootwads from on-site can reduce a project's cost. In most cases, material can be recycled from the clearing and grubbing phase. Do not burn those stumps, use them! Muster the resources to take advantage of dry weather and low-flow conditions to execute an expedient yet thorough construction sequence, especially if working in-the-wet.

Communicate, inform, and educate—Keep neighbors, stakeholders, visitors, and regulators informed as work progresses. Assign somebody to be on-site to intercept visitors, for their safety. Facilitate clear communications between the designer and contractor. For our most recent restoration, we took a lesson from incident management protocols by preparing a communications plan and holding a community open house. Proactive outreach to local media allowed us to deliver a targeted message while managing expectations.

Revegetate with authority—Stream restoration is more than what happens within the channel. Successful ecosystem functions are derived from re-establishing a riparian zone. Do not skimp on revegetation. Use a diversity of native plants. Live stakes can quickly establish a foothold along the streambanks. Protect tree seedlings with tube shelters. Incorporate native grasses. For us, salvaging and transplanting on-site shrubs has been effective; in most cases, the shrubs had to be removed anyway during the site grubbing. This idea originated with the restoration contractor.

Billboard accomplishments—Document the 'before' and 'during' phases with photographs to help tell the story afterward. Take advantage of imaging technology such as UAVs (i.e., drones) and videos. Make the restoration site available for training, education, and outreach, including social media. If the site is open for public viewing, install exhibit signs explaining, in simple terms, the basic story elements of who, what, why, and how.

Be vigilant for invasive species—Invasive vegetation can be easily introduced by equipment and material (e.g., straw for soil stabilization). Have contractors clean their equipment before entering the property. Frequently monitor the site and promptly control invasive plants and animals. This may prove to be the most resource-intensive management responsibility afterward.

Analyzing long-term effect of gully erosion on land degradation in Upper Blue Nile basin, Ethiopia

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Gully erosion is one of the main causes of land degradation, particularly in the drought-prone regions of Ethiopia. This study assessed spatio-temporal changes of gully length and density in watershed pairs in Guder, Aba Gerima, and Dibatie sites, which are representative highland, midland, and lowland agro-ecologies in the Upper Blue Nile basin of Ethiopia. Aerial photographs (1957, 1982) and very high resolution satellite images (QuickBird, IKONOS, Worldview-2, SPOT-7, and Pleiades) of the six watersheds, along with field survey results, were used in the analyses. The aerial photographs were scanned and orthorectified using ENVI 4.3 image analysis software, and gullies were mapped by visual image interpretation in the ArcGIS environment. Rates of increase in gully length in Guder (36.9 m yr^{-1}) and Aba Gerima (33.6 m yr^{-1}) were almost double the rate in Dibatie (17.8 m yr^{-1}) from 1957 to 2016 or 2017, and over the same period, gully density similarly increased by 5.9, 5.4, and 3.7 m ha^{-1} in Guder, Aba Gerima, and Dibatie, respectively. The higher rates in Guder and Aba Gerima could reflect the long history of cultivation and human settlement in those sites, whereas agricultural activity became widespread in Dibatie only after implementation of the national resettlement program in the 1980s. Moreover, although gully density tended to increase over time in all six watersheds, in the three watersheds (one in each paired watershed) where soil and water conservation measures had been introduced, the rate of increase was lower than in those where no such measures were implemented. In addition, gully distribution was linked to land use and landscape position; gully density was higher in cultivated areas and where slope gradients were gentle. The results of this study indicate that careful site-specific identification of factors controlling gully initiation and development is crucial so that appropriate management strategies can be developed for these three sites and for other areas with similar agro-ecologies in the Upper Blue Nile basin.

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Ecosystem water service of tropical island under the changing climate regimes and the altered land cover/use

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Impact of changes in land cover/ use and climate on hydrological service of tropical watersheds is one of the focal research tropics in both hydrology and global change. Both landscape composition and configuration are important features of LCLUC, and they interactively impact the hydrological service of tropical watersheds in the context of changes in climate regimes. Puerto Rico is a tropical island in the Caribbean, the freshwater supply from upland watersheds is essential in both meeting the demands of water consumption for over 3 million population and feeding the coastal wetlands to combat saltwater intrusion. The capability of sustainable freshwater supply is facing great challenge under changing climate regimes and land cover/ use over the island. To address this, we adopted the Soil and Water Assessment Tool (SWAT) model to the watersheds feeding major wetlands in both wet and dry regions, and investigated the ecohydrological processes in response to climate changes and LCLUC. We calculated annual stream discharge and annual big stream discharge with risks of flooding and severe soil erosion, defined as the sum of daily discharge greater than 95 percentiles. We emphasized how the changes in landscape composition and fragmentation, and the projected climate in the next 50 years will alter ecohydrological processes. Land cover change plays more important roles in regulating the big discharges (risk of flooding) than altering the annual discharges (freshwater supply). Based on the downscaled climate models for Puerto Rico (Hayhoe 2013) for IPCC 3 emission scenarios of A2 (isolated development, little collaboration), A1B (collaboration between countries with balanced energy use), and B1 (economic globalization with high technology development), the watersheds of Rio Grande de Loiza at Caguas in the mountains and Rio Culebrinas in the northwest both showed consistently decreasing discharge (freshwater supply) in the next 50 years. The average annual rate of decreasing is -0.64 and -1.27 M ton y^{-2} for Rio Grande Loiza and Rio Culebrinas watersheds, respectively. Prompt and rational management of freshwater resources over the island and of mountainous watersheds is mostly needed to tackle the impacts of changes in climate and land use/cover for sustainable ecosystem water services of the island.

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Section 5: Bedrock Flow and Reactions: Implications for Ecohydrology and Watershed Exports, Special Session

Groundwater Sourcing and Age Distributions in a Colorado River Headwater Stream

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Headwater basins of the Colorado River are vulnerable to climate change. Increasing air temperatures, longer lasting droughts, and climate induced forest die-off alter land-surface interactions, snow dynamics, and hydrologic partitioning in space and time. Changes in the timing, intensity and duration of water inputs directly impact groundwater recharge, subsurface flow paths and residence times with consequences for riverine water and solute exports. Feedbacks between these processes are poorly constrained in mountain watersheds due to a lack of data characterizing surface dynamics and subsurface properties. To combat data challenges, we combine high resolution snow observations with chemical and isotopic water concentrations, groundwater dissolved-gas tracers, and numeric models to explore first-order controls on groundwater flux to streams, age of hydrologically active groundwater, and baseflow age-distribution sensitivity across gradients in climate and watershed characteristics in a Colorado River headwater basin (24 km^2). Results indicate that groundwater is a critical and stable source of water to this mountain stream with preferential recharge zones established in the upper sub-alpine that are partially decoupled from annual climate variability and resilient to historic drought. Baseflow ages estimated using dissolved concentrations of SF_6, N_2, and Ar in stream water suggest a median age of approximately 10 years. This aligns with ages estimated with dissolved gases in perennial springs (7 ± 4 years), and in shallow (20 ± 12 years) and deep groundwater wells (50 ± 11 years). To match gas tracer age estimates, groundwater flow must be partitioned, in part, to deeper flow paths as dictated by hydraulic properties of the fractured granodiorite. Hydrologic model results also suggest the watershed operates on a precipitation threshold near the basin's historic median value. With drier conditions, the ratio of recharge to hydraulic conductivity is reduced, water tables drop, and the basin moves away from topographically-controlled groundwater flow toward recharge-controlled groundwater flow. Under these conditions, baseflow ages become older and increasingly sensitive to small changes in net recharge as a function of aridity or forest change. Therefore, as this mountain system moves toward more arid conditions, the compensatory effects of groundwater to mountain streams will shift toward longer timescales with implications on water and environmental management.

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A Scale-Aware Modeling Framework to Quantify Subsurface Geochemical Exports and River Water Quality

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To enable effective water resources management, watershed-scale models are needed for predictive understanding of downstream river water quality. However, watershed-scale models are computationally strenuous and inadequately represent finer-scale heterogeneity and, therefore, are likely to misrepresent critical processes. Here we present a scale-aware modeling framework harnessing the versatility of artificial intelligence and machine learning approaches along with mechanistic modeling to develop a predictive understanding of coupled surface- and sub-surface watershed-scale hydro-biogeochemical dynamics. This study aims at developing a scaling relationship between bi-directional exchange and biogeochemical transformations at the terrestrial–aquatic interfaces (TAIs) and across watershed and river landform features characterized by various sinuosity and amplitude of meanders, topography, and residence times. To capture bi-directional exchange and biogeochemical transformations at TAIs, we carried out three-dimensional reactive flow and transport simulations using a reactive transport solver – PFLOTRAN for a 10-meander system in the upper East River watershed. This area is part of the Watershed Function Scientific Focus Area Site of Berkeley Lab and is located within a high elevation catchment in western Colorado. Simulation results demonstrate that bi-directional exchange and biogeochemical transformations of redox species such as oxygen, nitrate, and iron follow the power-law nature of the distribution of sinuosity, amplitudes of meanders, and residence times. Results further demonstrate that scaling exponents typical for meanders are significantly different for oxidizing and reducing conditions. Efforts are underway to predict subsurface geochemical exports and downstream river water quality of the more extensive East River system by making use, in part, of the high-performance computing platforms provided by PFLOTRAN and the NERSC.

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Hysteresis Patterns of Watershed Nitrogen Retention and Loss over the past 50 years in United States Hydrologic Basins

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River corridor systems in snow-dominated, mountainous regions often express complex biogeochemistry and river water nutrient indicators as a function of hydrologic exchange variability and snowmelt conditions. Watershed ecological control points (ECPs) (e.g. hyporheic zones, riparian hollows, stream bed bedrock fractures) are important for solute and nutrient processing at small scales, yet can have major impacts on large scale watershed exports. A major motivating factor for our work is a five-year concentration-discharge (C-Q) time series which display declines in inorganic nitrogen over time as well as down the watershed network, indicating the importance of the passive versus active transient nature of these ECPs. In our research, we develop a predictive understanding of the subsurface and surface controls on hyporheic biogeochemical behavior through data-model integration. We investigate a loose-coupling strategy for hyporheic systems that allows river gross primary productivity (GPP), hillslope runoff, and bedrock contributions to augment hyporheic zone function. We apply this model to the hyporheic zone along the East River, Colorado. Across the hyporheic zone and floodplain, we measured surface and subsurface gases, geochemistry, isotopes, and used this data to constrain our model in the presence of transient hydrological flow conditions. A Bayesian approach was used for the river model that allows GPP, respiration, and diffusion parameters to vary with season, constrained by radiation, barometric pressure, water depth, temperature, pH, DIC, and atmospheric CO_2. These river simulations were used as boundary conditions to test the dynamic nature of the hyporheic zone in response to projected future temperature and atmospheric CO_2 representing carbon emission futures, and to compare future and current hyporheic zone processing. Our data coupled with the predictive power of our numerical model reveal that hyporheic zones can serve many different roles throughout the year and indicate the importance of hyporheic cycling as a critical control point on watershed scale exports. The reliance of active versus passive ECPs on the timing of meltwater infiltration, including the possibility of a longer vernal window under future climate change indicates the importance of ECPs as controls of river-based indicators of river corridor hydrobiogeochemical function.

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Modeling Reactive Transport, Weathering and Critical Zone Evolution at the Hillslope Scale

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The architecture of the critical zone results from the coupled interactions between bedrock weathering, regolith production and erosion. We present coupled numerical models of reactive transport, weathering and erosion at the hillslope scale to improve understanding of the evolution of critical zone architecture and the functioning of the critical zone. The modeling approach incorporates both vertical and lateral hydrologic flowpaths in saturated-unsaturated flow, chemical weathering, and geomorphic rules for soil production and transport. Alterations in both solid phase (plagioclase to clay) and water chemistry is tracked along hydrologic flowpaths. The resulting weathering patterns are strongly controlled by hydrologic forcing. In a dry end-member climate, weathering is shallow and surface-parallel, whereas in a wet end-member climate, weathering occurs to significant depths, controlled by the channel depth. Exploration of intermediate cases reveals that the weathering pattern is strongly governed by the ratio of the weathering front speed (controlled by the recharge rate), and the erosion rate. The system transitions between the dry and wet end-member behaviors at a weathering front speed to erosion ratio of approximately 1. While the behavior in the dry end-member case can be explained largely based on one-dimensional weathering front propagation, the wet end-member case cannot be realistically explained without invoking the role of lateral groundwater flow. We also consider the influence of deep circulating groundwater flow paths on critical zone evolution and the generation of weathered profiles.

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Spatial distribution of pyrite oxidation under valley and ridge

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The spatial distribution of weathered rock across landscapes strongly influences how water and solutes are routed throughout the landscape. The oxidative weathering of pyrite (OWP) is usually the earliest alteration reaction observed in many formations, which defines the regolith-bedrock interface. To understand the controls on the evolution of weathering profiles that underlie hilly and mountainous regions, we investigated the spatial distribution of the OWP reaction front at the Shale Hills catchment in central Pennsylvania using geochemical measurements on materials recovered from boreholes across the catchment. As a subcatchment of the Susquehanna Shale Hills Critical Zone Observatory, intensive field monitoring and measurements of surface water and groundwater hydrology and aqueous chemistry in the past decade allow us to test how the reaction front recorded in rock is related to flow path and solute fluxes.

The V-shaped Shale Hills catchment contains an ephemeral, westward-flowing stream. The bedrock of the catchment is mainly composed of Fe-rich, organic-poor Rose Hill shale (Silurian-aged) with more interbedded carbonate and sandstone near the outlet of the catchment. Under the ridge, the depletion of pyrite occurs sharply across a front above the water table, but OWP also occurs in haloes around deeper fractures in the saturated zone, presumably where those fractures are connected, allowing oxygenated water to flow. Under the valley, the OWP initiates at ~ 20 m below the water table and completes at ~ 6 m below the water table, which results in a ~ 14 m wide reaction front. Such a wide reaction front of OWP under the valley is consistent with the proposed flow path at Shale Hills: O_2-rich interflow occurring in the upper fractured zone (5–8 m below land surface) mixes with deeper O_2-poor groundwater along the stream channel. The concentrations of pyrite-derived sulfate and carbonate-derived divalent cations (Ca^{2+} and Mg^{2+}) increase downstream, which indicates the OWP and carbonate dissolution is highly coupled.

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Geospatial modeling approach to determine potential sinkhole risk probability and soil subsidence

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Abstract—Aquifers in the Southeast United States are covered by limestone/dolomite carbonate rock that dissolves in water and leads to increased risk of sinkhole formation. The goal of this study was to develop an automated geospatial model to determine spatial locations with high-risk potential for sinkholes. Geology, soil, land use, aquifer, groundwater depth, road, fault line, elevation, precipitation, and evapotranspiration data produced nine sinkhole vulnerability layers: subsidence or surface change, average aquifer well depth, groundwater vulnerability (DRASTIC), groundwater travel time, road density, aquifer media, geology type, slope, and land use types. Each layer was reclassified and assigned a value from 1 to 10 using the Delphi Method of Weight Assignment, according to its sinkhole vulnerability. The weighted layers were analyzed interpretively producing a Sinkhole Formation Vulnerability Raster. The sampling tool was used for accuracy assessment comparing the obtained result with historical sinkhole data, at 77-percent accuracy. Results of this study could be useful to watershed stakeholders for decision support.

INTRODUCTION

Collapse sinkhole occurrence is a general phenomenon around the globe (e.g., Baer and others 2018, Galloway and others 1999, Martinez and others 1998). With the prevalence of climate change and urbanization, a rise in the occurrence of sinkholes throughout the United States is being observed. According to the U.S. Geological Survey (USGS), more than $300 million is spent annually on sinkhole damage in the United States. It is increasingly important for land planners to be able to determine and minimize the risk of property damage and potential casualties a sinkhole could cause through their knowledge of probable sinkhole occurrence locations. Collapse sinkholes are generally formed by the dissolution of subsurface soluble rocks, creating cavities that collapse when insufficiently supported (Gutiérrez and others 2014, Parise 2008, Waltham and others 2005) by soil strength.

Gradual dissolution-induced and aquifer/groundwater table vacuum-created land subsidence that occurs before, during, and

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after the surface collapse of the sinkhole are a common association of sinkhole formation (Intrieri and others 2015, Jones and Blom 2014, Nof 2012, Nof and others 2013, Paine and others 2012). According to Atzori and others (2015), based on recent field examination and elastic modeling studies, in elastically behaving soils, sinkholes are formed at the periphery of the subsidence zones. Previous sinkhole modeling investigations (e.g., Abdulla and Goodings 1996, Baryakh and Fedoseev 2011, Keqiang and others 2004, Shviro and others 2017, Tharp 1999) predict various mechanical responses of the overlying layers to the growth and migration of the underlying cavities and thus its contribution to sinkhole formation. Around southern Georgia and northern Florida, the aquifer cavities are made primarily of a submerged carbonate platform. These soluble evaporite rocks cause ground subsidence (Cooper and others 2011, Dahm and others 2010, Thierry and others 2009). In this region, the carbonate rocks are made of limestone and dolostone (Kromhout 2017). The carbonate rock is capped by relatively insoluble sand and clay. The movement of water and other chemicals such as carbonic acid in the groundwater can cause erosion and the formation of underground cavities. This can cause the clay and sand above to subside and eventually cave in. The collapse of these cavities can be rapid or slow depending on the geological and hydrological processes that form them. According to the USGS Water Science School, sinkholes are formed due to the chemical weathering (dissolution) of soluble rocks because of climate (intense rainfall or drought causing the water table to fluctuate) and climate change impacts that are accelerated by human impacts on natural systems (USGS 2020). Due to rapid urbanization, there has been an increase in the occurrence of sinkholes (Scheidt and others 2005) attributed to increased contamination of groundwater resulting from excessive urban runoff. Other anthropogenic activities like groundwater withdrawal, altering the earth's surface, and well drilling can also trigger the formation of sinkholes (Kromhout 2017).

Many constantly changing anthropogenic and natural factors make certain areas more prone to sinkholes. Natural causes include: substrate/rock properties and dynamics (Gutiérrez and others 2008), e.g., solubility and strength; landscape evolution along coasts, e.g., inlets and bays (Basso and others 2013), due to higher solubility and lower strength of evaporite than carbonate karsts (János and others 2013); seismic events/earthquakes (Dahm and others 2011); and groundwater flow-affected by rainfall (recharge) (Gutiérrez and others 2005). Human-induced causes include: climatic change (János and others 2013); changes to drainage patterns (sinkhole frequency increases near drainages, fault, etc., (Ozdemir 2015); subsurface drainage that causes karst aquifers vulnerability due to pollution (acidification) (Gutiérrez and others 2014); overburden/sedimentary cover burying carbonatic bedrock outcrops (where there are pressurized aquifers, seismogenic faults, springs-lakes/ponds enriched with CO_2 and H_2S); upward erosion through vertical conduits (deep faults) from piping where there are acidic fluids (Caramanna and others 2008); water abstraction (water quantity depletion) (Frumkin and others 2011); and groundwater contamination (water quality) (Polemio and others 2009).

Major consequences of sinkholes are (i) topographic changes in streams and groundwater flow direction; (ii) major environmental consequences due to sinkhole openings, i.e., polluting groundwater when sinkholes open in superfund and landfill site locations; (iii) spewing of toxic chemicals from beneath the earth up to the surface; (iv) flooding; and (v) infrastructure damages, etc., to name a few. Identifying these high-risk areas of probable sinkhole formation is essential in prevention and undertaking mitigation measures. The goal of this study was to develop an automated geospatial model combining geospatial analyses based on several significant spatio-environmental layers to identify the high-risk areas within the region of south Georgia and north Florida that are vulnerable to sinkhole formation. The following natural and anthropogenic consequential layers were considered to analyze sinkhole formation probability: (1) subsidence or surface change, (2) average aquifer well depth, (3) groundwater vulnerability (DRASTIC), (4) groundwater travel time, (5) road density, (6) aquifer media (Suwannee Limestone), (7) geology type, (8) slope, and (9) land use types.

MATERIALS AND METHODS

Study Area

The study area is contained within the Ochlocknee River basin (fig. 1). The basin is located across southwest Georgia and north-central Florida. The drainage area encompasses approximately 6,300 square miles. For the initial study, three HUC 12 subwatersheds, located southwest of Tallahassee, FL, were chosen. These three subwatersheds are located within the larger study area. The initial study area was chosen due to its high concentration of known sinkholes. Florida Department of Environmental Protection recorded 228 reported sinkholes from 1948 to 2020 within this area of interest. Unfortunately, no open-source data for the Georgia portion of the river basin was available. The three subwatersheds chosen for the initial study accounted for a total of 88 recorded sinkholes by the State of Florida. Finally, a smaller study area, containing a

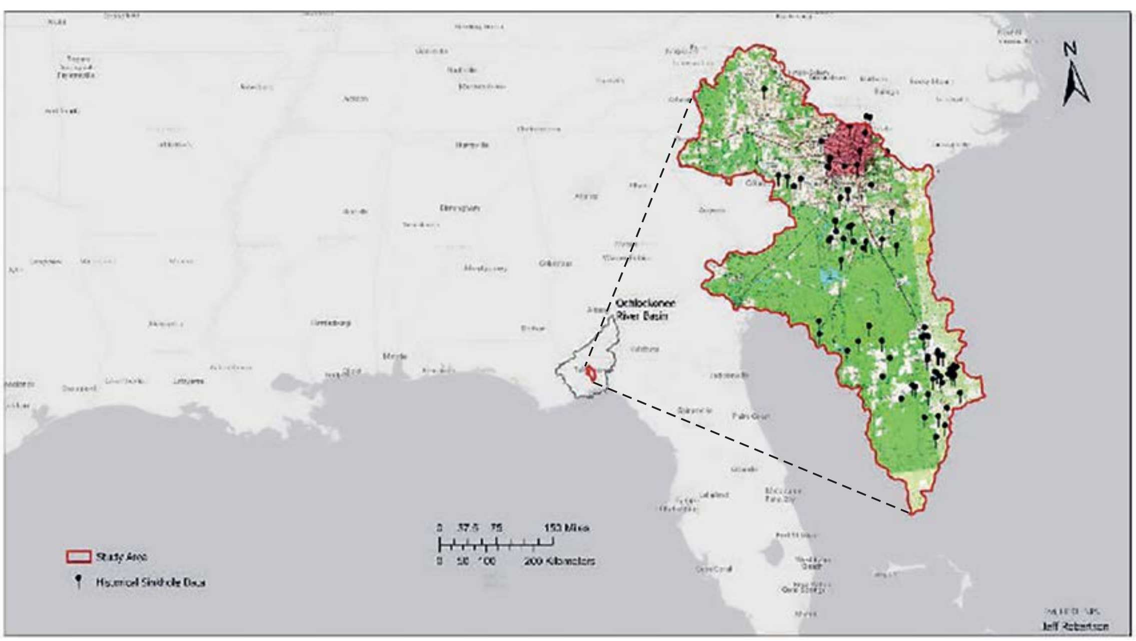


Figure 1—Study area map that encompasses southwest Georgia and north-central Florida.

higher concentration of known sinkholes, was chosen for accuracy assessment and calibration of the model that allowed for greater statistical analysis of the entire basin.

Data, Sources, and Tools/Software

Eleven types of geospatial data were collected, processed, and analyzed in ArcGIS Pro Model Builder to determine spatial sinkhole vulnerability in the study area. The data used in the developed automated geospatial model are geology, soil, land use, aquifer, groundwater depth, road, fault line, elevation, precipitation, and evapotranspiration. All these data were collected from USGS (https://www.usgs.gov/core-science-systems/ngp/tnm-delivery/gis-data-download), Florida Department of Environmental Protection (https://geodata.dep.state.fl.us/), and USDA Natural Resources Conservation Service (NRCS) Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/). From these data, nine sinkhole vulnerability layers were produced: (1) subsidence or surface change, (2) average aquifer well depth, (3) groundwater vulnerability (DRASTIC), (4) groundwater travel time, (5) road density, (6) aquifer media (Suwannee Limestone), (7) geology type, (8) slope, and (9) land use types. We used ArcGIS Pro 2.6 (ESRITM) software and its toolboxes, ModelBuilder platform and ArcPy programming platform, in the analysis.

Delphi Method of Weight Assignment

The Delphi method developed by the RAND Corporation in the 1950s aims to reduce the range of group responses and to strive for expert consensus, essential in environmental modeling where vulnerability/susceptibility/probability weight assignment is crucial. The Delphi method, group communication, and decision-making process is accomplished by the feedback of individual contributions of information and knowledge and response with a degree of anonymity to assign weights of vulnerability as applied in this study of determining sinkhole formation spatial probability (Adler and Ziglio 1996, Angus and others 1996, Linstone and Turoff 1975, Rowe and others 1991). Along with environmental impact assessments, the Delphi method is effective in various fields such as information systems, planning, social policy, public health, water resource use, and management, and water quality assessment (Angus and others 1996, Kim and Chung 2013, Lee and others 2013, Linstone and Turoff 1975, Okoli and Pawlowski 2004). We used the Delphi Method for developing weight index for individual layers that are associated with our sinkhole formation vulnerability model development. The team of authors along with a few professional experts were asked to provide their opinion on vulnerability weight scales for all nine individual layers used in the model development. Their weighted scale was compiled, and a consensus statistically derived weight scale was used for each layer. Another special weight scale was developed for the layers used in the DRASTIC model development to create the groundwater/aquifer contamination vulnerability layer.

Sinkholes Occurrence Probability Model Development

Subsidence or surface change vulnerability—Subsidence and surface change plays a key role in sinkhole vulnerability. Overconsumption of groundwater and urbanization have a direct impact on subsidence and surface changes.

This leads to a funneling effect of the contaminated surface water and accounts for changes to natural flow in the watershed. This limits the ability of the flora and fauna to naturally filter the carbon dioxide-rich runoff. The contaminated surface water then percolates as it travels through the soil. The carbon dioxide-rich water is transformed into a carbonic acid solution before it reaches the saturated zone of the aquifer. This increased drainage of acidic water accelerates the dissolution of the limestone aquifer layer. The resultant deterioration of the limestone can cause a collapse and may ultimately lead to a sinkhole. Historical topographic maps were obtained from https://livingatlas.arcgis.com/topoexplorer/index.html, digitized and converted into raster files using Topo to Raster tool of ArcGIS Pro 2.3 Toolbox for surface elevation change study. The maps that were used for this project were produced in the mid-1950s. Multiple maps had to be mosaiced to cover the entire study area. The initial step of this process was to digitize the maps' contour lines. Extra care was taken to outline water bodies and ridges. The completed shapefile had 389 line features. A separate shapefile was produced for the ground control data points. This consisted of 215 point features. To convert the feature classes to raster, the Topo to Raster tool was used. For this analysis, a 10-meter digital elevation model was created. Then, elevation changes were identified using the Minus tool, and a current (2010) LiDAR produced elevation map. The raster layer was then reclassified to create a subsidence or surface change vulnerability layer and table 2a represents the weighted scales of sinkhole formation vulnerability of the subsidence layer following the Delphi process.

Groundwater vulnerability—According to the USGS, 80 percent of subsidence in the United States is caused by excessive groundwater pumping (USGS 2020). As previously discussed, subsidence increases the chance of sinkhole formation. The Florida aquifer system is on a semi-annual well monitoring program. Measurements are taken in the spring and late summer to monitor and manage groundwater withdrawal levels. We used 153 measurements of well-depth data that were interpolated for the three studied HUC 12 subwatersheds. The larger area was then clipped to contain only the study area. The Kriging interpolation tool was used to interpolate a raster surface layer of groundwater table depth. The Kriging interpolation tool is effective when the observation of other hydraulic properties is limited (Jang and others 2017). The water table depth ranged from 10 feet to as deep as 152 feet. According to the Florida Aquifer Vulnerability Assessment, 48 feet or shallower water tables have the highest sinkhole vulnerability. The well-depth raster was reclassified for different depth ranges using the Jenks algorithm. Table 2b represents the weighted scales of sinkhole formation vulnerability of the layer as obtained via the Delphi process.

Aquifer vulnerability model layer (DRASTIC)—A DRASTIC model looks at seven environmental conditions that can determine aquifer vulnerability due to surface pollutants (Babiker and others 2005). The aquifer limestone geology is vulnerable to these pollutants. The factors are the Depth of the water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic Conductivity.

A consensual model DRASTIC vulnerability rating equation used for determining groundwater contamination vulnerability is as shown in equation (1):

$$\text{DRASTIC index} = 5Dr + 4Rr + 3Ar + 2Sr + Tr + 5Ir + 3Cr \qquad (1)$$

where r represents the rating of individual factors of D, R, A, S, T, I, and C as explained above.

Depth of groundwater (D) is the depth of the water table in feet (Machdar and others 2018) calculated from USGS data of groundwater wells (https://waterdata.usgs.gov/nwis). The Kriging interpolation tool was used to interpolate the well location data to create the well-depth raster of the study area. The deeper the water table, the farther the contamination must travel to reach the aquifer. Net recharge (R) is the amount of precipitation subtracted by the sum of the evapotranspiration and runoff. This is also used for the calculation of water infiltration into the soil. This is important since the water is a transport for pollutants. Net recharge was calculated by obtaining annual average precipitation PRISM raster (1980–2010 average) from USDA NRCS Geospatial Data Gateway, annual actual evapotranspiration raster from ESRI Living Atlas (https://www.esri.com/arcgis-blog/products/natural-resources/natural-resources/global-evapotranspiration-data-added-to-living-atlas/) and runoff (Q) raster developed through the use of USDA Curve Number (CN)-based algorithm (USDA NRCS 1986). Study area runoff was calculated using the CN algorithm, which is based on soil type, vegetation cover, impervious surfaces, interception, and surface storage analysis. A CN raster was initially created using reclassified land cover raster and reclassified soil (gSSURGO) raster for its Hydrologic Group (HG) properties to make it compatible with the USDA ARS table of CN value associated with the land cover and soil hydrologic group combination. Land cover raster was reclassifying into seven different categories with values ranging from 10 to 70, and the gSSURGO HG characteristic raster was reclassified with a numeric value from 1 to 4 representing A to D of the HG. The ArcGIS Plus tool was used to combine both reclassified land use with soil HG rasters. The combined raster was again reclassified with associating actual CN values for the individual combination of land cover type and soil HG type to produce CN raster following the USDA training manual https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/training/runoff-curve-numbers1.pdf. Using the Raster Calculator, the CN raster was used to calculate the potential for maximum retention after the runoff, S raster. The S raster was multiplied by 0.2 to determine the amount of infiltration or interception by vegetation during a rain event. The precipitation, P raster, along with the P and I_a rasters were then used to calculate runoff, Q raster. Finally, the Q, P, and ET rasters were map-algebraically analyzed using Raster Calculator to obtain R raster. It was reclassified into five groups using the Percentile algorithm in ArcGIS. The higher range received the higher values for groundwater contamination vulnerability.

The aquifer media (A) is the layer of the aquifer that controls leaching. USGS digital surface and hydrologic data was used for determining the aquifer media. The study area's aquifer media was made up entirely of limestone. Normally, the layer would be reclassed with a value of 8. However, this layer was given a value of 10 since the dissolving of limestone is a key factor for the formation of sinkholes. The soil layer is important for controlling the movement of recharge (Babiker and others 2005). The soils raster was created using the Reclassify tool of ArcGIS and the gSSURGO's permeability characteristics. During the reclassification process, different ranges of permeability were assigned with scaled values. The topography (T) layer gives values according to the slope. Areas with high slopes have a lower potential for contamination. Areas with low slopes have the potential to hold groundwater, which makes infiltration of groundwater and contamination more likely (Machdar and others 2018). This layer was built using LiDAR elevation data. The Slope tool was used to calculate slope gradients. The slope raster was reclassified, and scaled values were provided to ranges of slope gradient. The impact of the vadose zone media (I) has a similar function as the soil layer. The amount of potential contamination that could affect the aquifer layers is determined based on the layer's characteristics. The more porous the soil, the higher the potential for impact to the aquifer. For this layer, USGS Geology data was used and reclassified assigning weighted values. Hydraulic conductivity (C) is the ability of the aquifer material to repel water (Aller and others 1986). The higher the conductivity, the more porous the material. The lower the conductivity of the material, the less of a chance for contamination. The reclassification tool was used to reclassify gSSURGO Ksat values. Table 1a–g shows the Delphi-based weight assigned to each factor development scaled values of the DRASTIC model.

Table 1—Delphi-based groundwater contamination vulnerability scaled values for (a) depth of groundwater, (b) net recharge, (c) aquifer media, (d) soil media, (e) topography, (f) impact of the vadose zone, and (g) hydraulic conductivity

Depth of groundwater *(feet)*	Value
5–15	9
15–30	7
30–50	5
50–75	3
75–100	2
100+	1

(a)

Net recharger *(inches per year)*	Value
10+	10
7–10	8
4–7	6
2–4	3
0–2	1

(b)

Aquifer media	Value
Limestone	10

(c)

Soil media	Value
Sand	9
Loam	5
Silt loam, sandy clay loam, sandy clay	4

(d)

Topography *(% slope)*	Value
0–2	10
2–6	9
6–12	5
12–18	2
18+	1

(e)

Vadose zone media	Value
Beach sand	8
Limestone	6
Sand or clay	5

(f)

Hydraulic conductivity *(GPD/FT)*	Value
2,000+	10
1,000–2,000	8
700–1,000	6
300–700	4
100–300	2
1–100	1

(g)

All these seven reclassified rasters were combined using the Raster Calculator tool with the equation (1) algorithm. The DRASTIC model value was then reclassified using the Delphi-based weighted scale developed by the research team. The higher DRASTIC scores represent an increase in sinkhole vulnerability. Table 2b represents the weighted scales of sinkhole formation vulnerability of the layer as obtained via the Delphi process. Table 2c represents the DRASTIC-based groundwater contamination vulnerability scale that determines sinkhole formation vulnerability.

Travel time vulnerability layer—The Travel time analysis for groundwater movement in soil media is an important characteristic that determines the sinkhole formation vulnerability. An automated geospatial model (fig. 2) was developed based upon top-down analysis of a confined aquifer. The vulnerability to the aquifer is based upon the amount of time for a surface contaminant to reach the saturated zone of the aquifer. The model is based on the following parameters: sediment thickness, hydraulic conductivity, and impact of karst topography on travel

Table 2—Individual layer vulnerability scale as determined using the Delphi-based analysis: (a) topographic change, (b) groundwater table depth, (c) DRASTIC-based groundwater contamination, (d) travel time, (e) road density, (f) soil and geology types, and (g) land use/land cover type vulnerabilities

Topographic change vulnerability	Value
Negative change	5
Positive or no change	1

(a)

Water depth *(feet)*	Value
0–48	10
48–53	8
53–153	1

(b)

DRASTIC index	Value
199–300	10
179–199	9
159–179	8
139–159	6
119–139	5
100–119	3
79–100	2
0–79	1

(c)

Travel time 10^5 *(cm/sec)*	Value
0–62	10
62–124	9
124–186	8
186–248	7
248–310	6
310–373	5
373–435	4
435–497	2
497+	1

(d)

Road density	Value
High	5
Medium-high	4
Medium	3
Low-medium	2
Low	1
Pencils	2

(e)

Soil type	Value
Sand	9
Loamy	5
Fine-loamy	4

Geology type	Value
Beach sand	8
Limestone	6
Clay or mud	5

(f)

Item	Value
Developed	5
Wetlands	4
Barren	3
Agricultural land	2
Forest	1

(g)

Note: DRASTIC model slope-based vulnerability scaled raster was used for the seventh layer.

Note: As there was no fault line adjacent to the study area that would highly impact the sinkhole formation vulnerability, the Seismic Impact layer was not used.

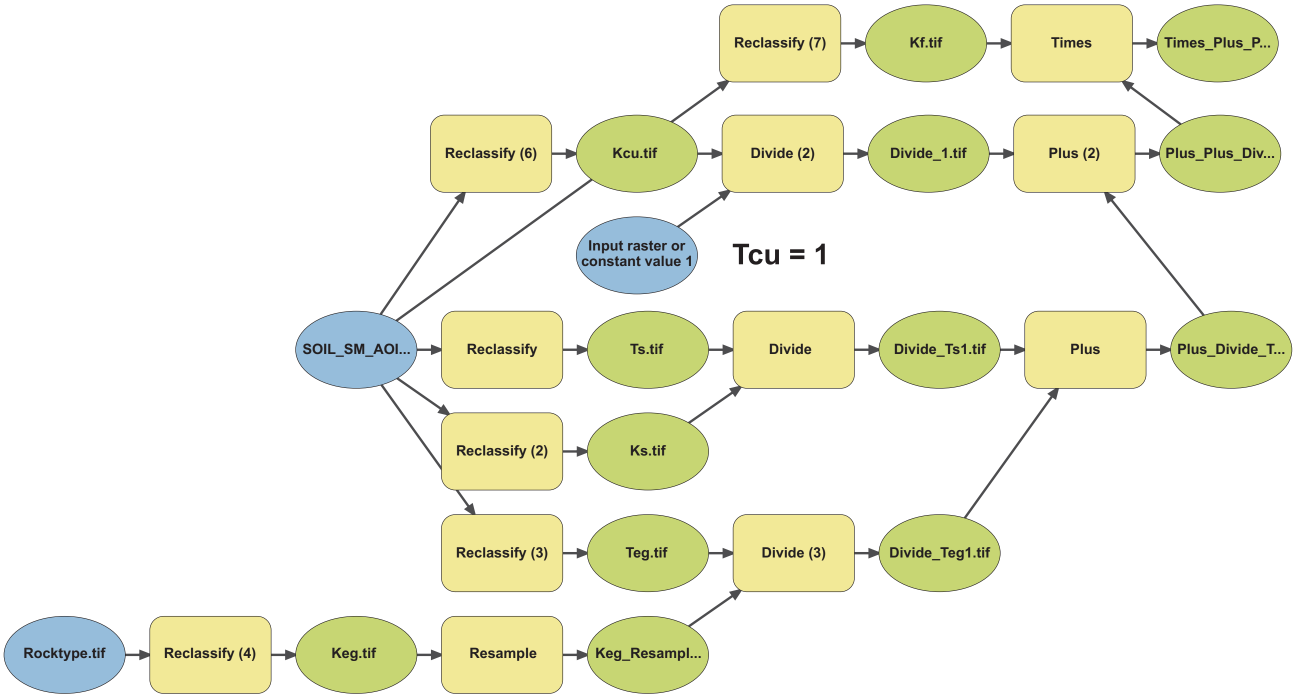


Figure 2—Travel time layer development process model in ArcGIS Pro 2.3 ModelBuilder platform that can be replicated and modified at ease.

time (FAVA). The travel time model is based on the following equation:

$$Travel\ Time = \left(\frac{Ts}{Ks} + \frac{Teg}{Keg} + \frac{Tc}{Kc}\right) * Kf \qquad (2)$$

where:

Ts = Soil Thickness

Ks = Soil Hydraulic Conductivity

Teg = Environmental Geology Thickness

Keg = Environmental Geology Hydraulic Conductivity

Tc = Confinement Thickness

Kc = Confinement Hydraulic Conductivity

Kf = Karst Factor

Soil Thickness in this model was derived from *Ts*, *Teg*, and *Tc*. Where *Ts* is a variable taken directly from the gSSURGO dataset, *Teg* is calculated by the difference in the bottom of the soil layer and the top of the confining unit, and *Tc* is the thickness of the confining unit. *Kf* serves to account for the decrease in travel time, a variable from the gSSURGO dataset. The *Ks* factor is a variable taken from the gSSURGO dataset. These values represent average values for lithotypes of environmental geology. *Kc* and *Keg* are both variables taken from the gSSURGO dataset and the Geology dataset. They are average hydraulic conductivity values of geology and confinement unit, respectively. Table 2d represents the uniquely and innovatively developed travel time vulnerability scale that determines sinkhole formation vulnerability.

Road density—Impervious surfaces increase and change the natural flow of stormwater. Without proper management, this runoff can cause rapid inflation and an increased risk of sinkholes. ArcGIS's Line Density tool was used to calculate the road polylines that surround each cell. These values were then reclassified based on its vulnerability towards sinkhole formation. The areas with the highest density were given higher values due to the possibility of high storm runoff from impervious surfaces as shown in table 2e.

Soil and geology—The rate at which water flows through the soil can play a big part in the formation of sinkholes. Large soil grain size equals higher permeability. When underground pipes and septic tanks leak in soils with high permeability, sub-terrain events can increase. Permeability data is not available for urban areas. Soil and geology types determine the sinkhole formation vulnerability, and table 2f represents the Delphi-based weighted scale.

Slope—Improper slope grades do not allow for the proper flow of surface and subsurface stormwater. This can cause water to pool. A slope raster with its weighted scale from the DRASTIC model was reused to emphasize it.

Land use/land cover—Land use changes lead to change in topography and geomorphology (Al-Kouri and others 2013). To emphasize these changes, a land use vulnerability layer was created with reclassified vulnerability scaled values assigned to it as shown in table 2g.

Seismic impact—There was no fault line adjacent to the study area that would critically impact the sinkhole formation vulnerability. Therefore, we did not use the Seismic Impact analysis as a layer to determine the sinkhole vulnerability layer.

Sinkhole Formation Vulnerability Model Development

Eight raster layers scaled to pixel levels are presented in table 2. As mentioned earlier, they were developed using Delphi-based analyses. An automated geospatial model was developed in the ArcGIS Pro 2.3 ModelBuilder platform for creating the eight individual layers and combining them using the Weighted Sum tool of ArcGIS to create the sinkhole's formation spatial vulnerability raster. Figure 3 shows the entire geospatial modeling process that can be modified and replicated at ease.

RESULTS AND DISCUSSION

Individual Layer Analyses and Sinkhole Formation Vulnerability Raster

Figure 3 is the schematic architecture of the automated geospatial model in its entirety as developed to obtain the sinkhole formation spatial vulnerability, and figures 4a–i are the individual vulnerability layer maps.

Each raster was reclassified with the vulnerability scale that was designed by the research team using the Delphi-based weight development process and shown in table 2. The final output of the comprehensive automated model was the sinkhole formation vulnerability spatial distribution raster. As the automated model has the immense efficiency of modifying it with ease, we have developed several sinkhole formation vulnerability rasters, such as High-value Travel Time and Low-value DRASTIC along with other layers as fixed (fig. 5a); High-value Travel Time and No DRASTIC along with other layers as fixed (fig. 5b); and DRASTIC and Travel Time layers weighted equally keeping other layers as proposed (fig. 5c). Each raster was classified into five classes using the Jenks algorithm. Deep red and red-colored areas on the maps represent locations of higher probability for sinkhole formation. It is to be noted that the southeast side of the subwatershed has the highest vulnerability for sinkhole formation showing high-density historical sinkholes formed there. The central part of the subwatershed shows higher vulnerability for future sinkhole development.

Figure 3—Schematic of the automated geospatial model showing the process to develop the sinkhole formation spatial vulnerability.

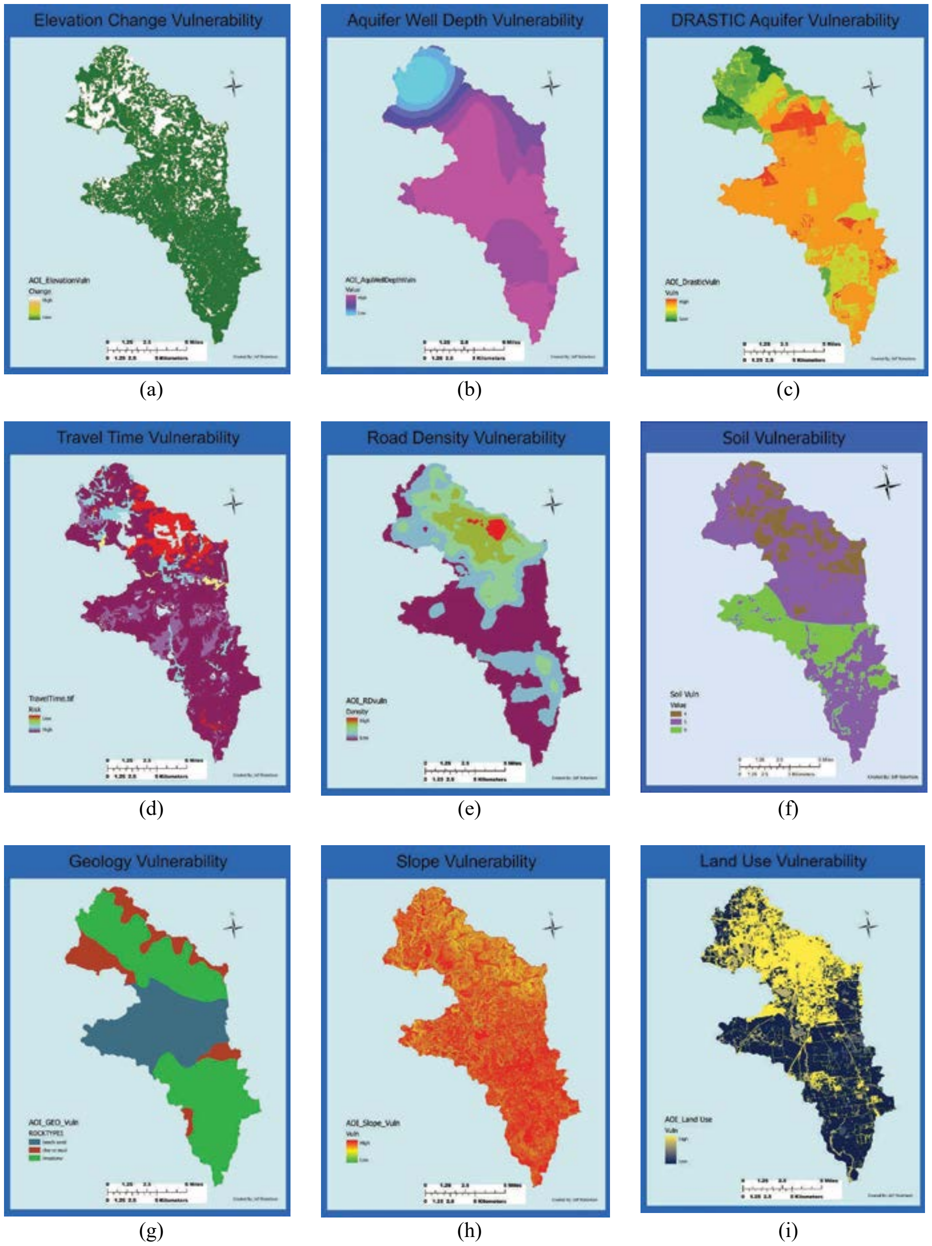
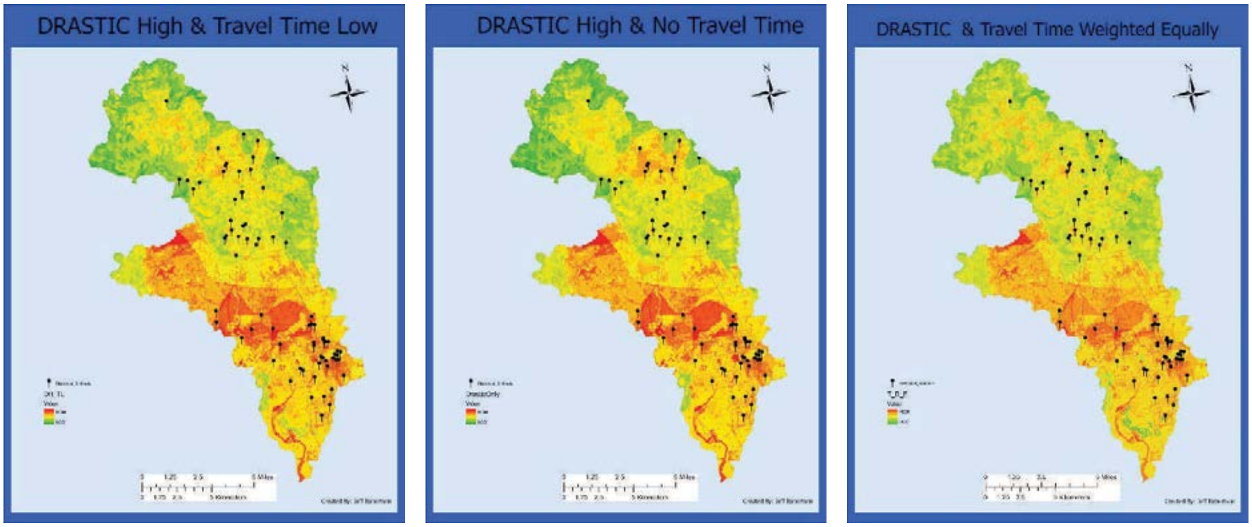


Figure 4—Individual layer rasters that are reclassified later in the automated geospatial model per the Delphi-based sinkhole formation vulnerability scale index as shown in table 2a–g.

Accuracy Assessment

To determine the accuracy of our model, the Known-Point Sampling method was initially used. This method analyzes pixel location in comparison to the final sinkhole vulnerability layer. The cell that the known point pixels fall within is then calculated to find which cell has a pixel value equal to or greater than a specified value. In the initial run of this model, before calibration completion, the median value in the vulnerability raster was used, a value of 25. For this assessment if the value was greater, a sinkhole was predicted, if it was less, a



(a) (b) (c)

Figure 5a-c—Study area sinkhole formation vulnerability spatial distribution rasters showing the accuracy assessment results in percent.

sinkhole was deemed unlikely. The initial accuracy assessment for the uncalibrated model found an accuracy of 77 percent (fig. 5a) for known sinkhole locations. After completing the calibration of the model, this method was modified to gain a result that was more representative of the data.

This updated method for the calibrated model reclassified the final sinkhole vulnerability layer into 5 classes, 1 being least likely for sinkhole formation and 5 being the most likely. This layer was then sampled using the 85 known historical sinkhole points within our study area; the results from this method found 72 known sinkholes were predicted at a rating of 4–5, 12 sinkholes were given a rating of 3, and only 1 sinkhole was given a rating below 3. Overall, this gives an accuracy rating of 84.7 percent (fig. 5b) of known sinkholes that fell within the high to very high category for sinkhole vulnerability. The accuracy increased further to 87.1 percent when we weighted DRASTIC and Travel Time layers equally.

CONCLUSION

The results of this study provide a promising method for predicting sinkhole vulnerability. An accuracy rating of ~ 87 percent is encouraging for this study, and further development and calibration may increase accuracy. The use of both the DRASTIC model and the Travel Time model provides greater insight into what may cause sinkhole formation. Increasing understanding about the formation of these can help better prepare the public and encourage change within society to prevent unnecessary damage from this naturally occurring phenomena. Providing a method for identification of areas at higher risk will allow the public to prepare and possibly prevent sinkhole formation that can cause severe structural damage and possibly loss of life.

In this study area, promising results were found that were created solely using publicly available data. This method could be recreated in areas where established methods are not applicable or possible. Using two uniquely and innovatively developed methods such as the DRASTIC model and the Travel Time model allows for the development of potent analysis tools that can provide a much needed service in predicting sinkhole formation. Sinkholes are a problem wherever there is karst topography and providing the public with a method to predict sinkhole formation is a necessity. Analyzing what causes their formation and predicting where they are likely to form is a crucial step to facilitating change that may slow down the formation of future sinkholes.

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Section 6: Remote Sensing of Watersheds and Riparian Systems

Soil moisture monitoring at ARS Long-Term Agroecosystem Research sites

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USDA-ARS

Soil moisture monitoring has experienced a great increase in visibility and importance with the advent of recent satellite missions. In 2002, soil moisture monitoring began in earnest across several watersheds operated by the Agricultural Research Service, including Walnut Gulch (AZ), Little Washita (OK), Little River (GA), and Reynolds Creek (ID). These networks were able to establish the baseline accuracy of the AMSR-E product with an accuracy of 0.06 m^3/m^3 which met the mission requirement. Two additional missions with improved performance characteristics further demonstrated the utility of the watersheds for calibration and validating global soil moisture products. In 2012, the Soil Moisture Ocean Salinity mission was validated using these ARS watersheds with an accuracy of 0.043 m^3/m^3. In 2015, the Soil Moisture Active Passive (SMAP) mission was launched with the largest coordinated cal/val program yet to be established for soil moisture. A total of six ARS watersheds were included in the set of core validation sites out of fifteen total and the overall accuracy was demonstrated to be 0.038 m^3/m^3. When SMAP produced a new 9km soil moisture product, ARS watersheds again provided the necessary data records for calibration and validation, proving the accuracy of the new products to be 0.037 m^3/m^3. The utility of improved soil moisture products has provided for great advances in hydrologic science and benefitting society in a multitude of ways. Soil moisture satellite products are being used to improve drought analysis. Soil moisture products from SMOS and SMAP have been used to improved flood forecasting as well. Soil moisture products are being incorporated operationally to improved continental National Weather Service Noah Models. Currently eight ARS watersheds are conducting satellite scale soil moisture calibration and validation activities at increasingly smaller scales, bringing soil moisture monitoring down eventually to the management scale. This presentation will be a review of the impact and value of soil moisture monitoring at ARS Long Term Agro-ecosystem Research sites.

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The nature of land-cover changes to aquatic buffers in the Midwestern USA: 25 years of Landsat analyses (1993–2017)

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Important biogeochemical processing and flow-attenuation occurs in surface and near-surface inflows surrounding – or buffering – aquatic systems. Hence, modifications to areas buffering waters can have profound impacts on quantity, quality, and seasonal inundation in a given water body, as well as implications for the condition of downstream systems. To understand timing, extent, magnitude, and frequency of change in buffer areas (90-meter) surrounding waters of the Midwestern US, we analyzed the full archive of three Landsat path/row image combinations totaling 31 years of data for ~100,000 km^2, including areas of high urbanization (i.e., Chicago, IL, and St. Louis, MO) and agriculturally dominated landscapes (i.e., Peoria, IL). We used the Continuous Change Detection and Classification (CCDC) algorithm, which identified instances of land-use/land-cover (LULC) change throughout the continuous Landsat archive for each 30-m pixel. We trained a random forest classification algorithm using the 2001 National Land Cover Dataset, binned the data into six LULC classes, and analyzed continuous LULC change with CCDC from 1993–2017.

Though relatively small as a percent of the image, the spatial extent of the LULC modifications is substantial (e.g., developed lands increased by 280 km^2 in the Chicago image, whereas ~ 300 km^2 of forested land was converted to other LULCs in the St. Louis image). While change was consistent for the ~ 110,000 waterbody buffers analyzed across all three images, LULC change in buffering areas frequently occurred at much greater rates than LULC change calculated image-wide. For instance, buffer LULC changed to developed lands at 2x the rate in the Chicago image and 3x in the Peoria image. Forested and grasslands buffering waters were converted to other LULCs at 7x and 3x, respectively, the image-wide rate of change in the Chicago image. However, not all LULC change was conversion to development or agricultural classes, as waterbody expansion in the buffers occurred at rates of 13–70x image-wide rates across the three images. The greatest change occurred most frequently in buffers surrounding the smallest waters (<0.1 ha), though this varied by image.

Changes wrought to areas buffering waters likely affect processes within a given water as well as cumulatively modify downstream conditions. Therefore, incorporating water buffer LULC dynamics into large-scale modeling and empirical studies will improve the physical representation of the landscape and affect research on aquatic nutrient and hydrologic dynamics.

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Fine-resolution mapping of surface water and wetland inundation dynamics in the Prairie Pothole Region

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The Prairie Pothole Region of North America is characterized by millions of depressional wetlands, which provide critical habitats for globally significant populations of migratory waterfowl and other wildlife species. Due to their relatively small size and shallow depth, these wetlands are highly sensitive to climate variability and anthropogenic changes, exhibiting inter- and intra-annual inundation dynamics. Moderate-resolution satellite imagery (e.g., Landsat, Sentinel) alone cannot be used to effectively delineate these small depressional wetlands. By integrating fine spatial resolution Light Detection and Ranging (LiDAR) data and multi-temporal (2009–2017) aerial images, we developed a fully automated approach to delineate wetland inundation extent at watershed scales using Google Earth Engine. Machine learning algorithms were used to classify aerial imagery with additional spectral indices to extract potential wetland inundation areas, which were further refined using LiDAR-derived landform depressions. The wetland delineation results were then compared to the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) geospatial dataset and existing global-scale surface water products to evaluate the performance of the proposed method. We tested the workflow on 993 HUC-10 watersheds with a total area of 750,000 km^2 in the Prairie Pothole Region. The results showed that the proposed method can not only delineate the most up-to-date wetland inundation status, but also demonstrate wetland hydrological dynamics, such as wetland coalescence through fill-spill hydrological processes. Our automated algorithm provides a practical, reproducible, and scalable framework, which can be easily adapted to delineate wetland inundation dynamics at broad geographic scales.

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Actions and plans to quantify the “Invisible Giant” – Evapotranspiration – in Florida water budgets

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The U.S. Geological Survey (USGS) Caribbean-Florida Water Science Center has pursued a multi-decadal strategy to better quantify evapotranspiration throughout the State of Florida. Evapotranspiration – a substantive component of the water budget accounting for roughly 75 percent of annual rainfall in Florida – warrants this pursuit. USGS efforts in Florida to quantify evapotranspiration began in the 1990s with a network of micrometeorological stations to measure the evapotranspiration flux at high resolution (daily to sub-daily) at the field scale, providing substantive data on this elusive component of the water budget and its relation to environmental variables of land cover, solar insolation, weather/climate, and water availability. Beginning in 2005, the USGS and partners merged high resolution spatially-distributed, satellite-derived solar insolation data with field- and North American Regional Reanalysis-derived meteorological data to provide spatially- and temporally-continuous surrogates of daily evapotranspiration – reference and potential evapotranspiration – at 2-kilometer resolution throughout the State of Florida. These data are critical drivers of estimates of agricultural water use and of hydrologic simulation for the purpose of water management. The quality of spatially- and temporally-continuous satellite-derived actual evapotranspiration over Florida, as estimated by the USGS Simplified Surface Energy Balance – operational (SSEBop) approach, is now being evaluated through independent estimates of actual evapotranspiration – from water budget estimates and micrometeorological station measurements. Future studies include “mining” of the actual evapotranspiration product SSEBop to derive functional relations between evapotranspiration and environmental drivers, expansion of the geographic domain of these efforts to include areas of adjacent states to allow seamless inter-state hydrologic analyses, and projection of evapotranspiration estimates into the future to acknowledge climate and landscape changes.

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Remote-sensed Demonstration of Ecosystem Services in the Great Pee Dee Basin, South Carolina

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The Great Pee Dee watershed in northeastern South Carolina contains over 600,000 acres of floodplain forests, which provide important ecosystem services of flood retention and pollutant capture. The Nature Conservancy and partners endeavored to demonstrate pollutant capture services to a broad range of Great Pee Dee stakeholders whose support is important to its mission of natural land conservation. This desired support is both political and financial. However, demonstrating ecosystem services for water quality is very difficult with traditional sampling approaches. Advances in remote sensing of water quality are overcoming the challenge of identifying source and sink areas of various point and non-point source pollutants. In this project, we employed remote-sensed water quality images and post-processing to demonstrate turbidity capture services performed by floodplain forests along the Great Pee Dee. Turbidity in river flows passing through forested floodplain reaches was consistently reduced across four discrete hydrologic events including large and small regional floods, and thunderstorm-driven pulses. This visually-driven portrayal of ecosystem services in action was also very engaging for river stakeholders, and is spurring conservation action for land protection and management in the watershed.

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An evaluation of ECOSTRESS products on a temperate montane humid forest

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Mountain landscapes provide water for much of the World's population, but plant water use trajectories are difficult to predict in complex terrain with high species diversity. Technologies embodied in NASA's Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission may provide critical data for understanding hydrologic cycling in these forested mountain areas. Measurements from eddy flux towers have provided the bulk of performance evaluation for ECOSTRESS data products to-date, but most flux towers are located in flat terrain, sampling relatively homogeneous vegetation. In this study, the accuracy of ECOSTRESS' Level 2 instantaneous Land Surface Temperature (LST) and Level 3 PT-JPL evapotranspiration (ET) estimates were evaluated against an eddy covariance tower and five climate stations at the USDA Forest Service's Coweeta Hydrologic Laboratory, located in the southern Appalachian Mountains of western North Carolina. Frequent cloud cover limited ECOSTRESS data, there were 30 of 100 cloud masking images that covered more than 80% of the study area by the end of 2019. We compared the hourly surface air temperature observations at the five climate stations with ECOSTESS LST, and found that they agreed reasonably well ($R^2 = 0.86$ and $P < 0.001$ for the high-quality ECOSTESS measurements, clear sky and accuracy < 2 °C). For instantaneous ET, there were only sixteen estimates (50% of valid LST estimates with clear sky and accuracy < 2 °C) at our study site. We found that ECOSTRESS tended to consistently overestimate both instantaneous and daily ET, which may mainly result from the coarse ancillary inputs and the diurnal cycling upscaling method. Our study comprehensively evaluated the accuracy of ECOSTRESS products and pointed out the possible error sources, which will help ECOSTRESS mission to improve the accuracy of ECOSTRESS products further and provide a reference for other ECOSTRESS data users.

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Section 7: FACETS: Floridan Aquifer Collaborative Engagement for Sustainability, Special Session

Stakeholder-Driven Modeling in Support of Groundwater Sustainability: the Floridan Aquifer Collaborative Engagement for Sustainability (FACETS) Project

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The Upper Floridan Aquifer (UFA) is among the largest, most productive aquifers in the world and is a vital regional resource shared between Florida, Georgia, and Alabama. The UFA supports agricultural activities worth > $7.5 billion and supplies drinking water to more than 10 million people but faces significant threats to water quality and quantity, which could potentially harm food security, fiber production, and vital ecosystem services. The Floridan Aquifer Collaborative Engagement for Sustainability (FACETS) project is bringing scientists and a diverse group of stakeholders together in a Participatory Modeling Process (PMP) to understand the economic-environmental tradeoffs associated with alternative climate, land use, Best Management Practice (BMP) adoption, and policy scenarios, with the ultimate goal of understanding changes needed to achieve agricultural water security and environmental protection. Scenario analyses results are being incorporated into public willingness-to-pay and producer willing-to-accept surveys to develop BMP adoption/land use change supply and demand curves, which will inform the development of policies and incentives to bring about changes in land use and water management. This session will highlight successes and challenges of the first two years of this five-year project including field experiments to measure yields as well as water and nutrient balances of alternative cropping systems and BMPS; co-development of biophysical and economic models to simulate agricultural/silvicultural production, water quality and quantity, and economic conditions for baseline and alternative future scenarios in the region; and use of social learning research to shape the design of the Participatory Modeling Process.

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Predicting Precision Nitrogen Side-dress Applications for Maize with a Simulation Model

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Consistent maize (Zea mays L.) yields of near 16,000 kg/ha is a goal of many growers in the state of Georgia, USA. To achieve this goal, a common practice is to increase the application rates of fertilizers and irrigation water. However, recent experiments conducted in this area have shown that nutrients and water are not always the limiting factors in achieving higher yields and that high fertilizer rates result in nonpoint source pollution, particularly critical in watersheds areas.

This research focus on increasing nitrogen use efficiency (NUE) by using the STICS (Simulateur mulTIdiscipli-naire pour les Cultures Standard) model (INRA, France) to simulate plant uptake and soil nitrogen dynamics to estimate the need of side-dress nitrogen applications. The model was selected for its high adaptability compared to most similar models. Model inputs include general parameters, plant parameters, soil parameters, initial conditions, crop management information and weather data. Model outputs include soil water content (mm^3 mm^{-3}) and soil NH_4^+ and NO_3^- (kg ha^{-1}). The model was calibrated and validated using data from a study conducted during 2018 in southern Georgia, where nine combinations of six management strategies – three fertilization and three irrigation management strategies, were tested.

The experiment was repeated, and the model validated, during 2019 using a fertilization treatment with five side-dress applications scheduled according to model predictions of soil mineral N. Overall, model validation was determined to be good as values of the evaluation indices were similar to those from calibration. The presentation describes the model performances. Following the 2019 experiment, the model will be incorporated into the SmartIrrigation Corn App, a smartphone application for scheduling irrigation in corn. The modified application will allow growers to schedule both irrigation and side-dress applications of nitrogen increasing profitability and sustainability. This research is part of the FACETS (Floridian Aquifer Collaborative Engagement and Sustainability) project funded by a grant from the United Stated Department of Agriculture – National Institute of Food and Agriculture.

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Economics of Best Management Practices to Improve Water Quality and Quantity in the Upper Floridan Aquifer

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Long-term economic and environmental sustainability of agriculture is necessary for its economic contribution to southwest Georgia, north central Florida and southeast Alabama; an area where the Upper Floridan Aquifer (UFA) is a vital resource of water. As populations and demand for water increases, water security has become an issue to agricultural and residential users. As a result, environmental regulations to ensure water quality and availability were signed into law and litigation between Georgia and Florida escalated to the United States Supreme Court. Water use and management practices are critical to the future of the landscape supported by the UFA. Alternative land use practices need to be identified and implemented to improve water quality and ensure water use efficiency. By interviewing extension agents and agricultural producers, enterprise budgets were developed to reflect the current land use management practices in the UFA for cotton, peanuts, corn, hay and pasture. These enterprise budgets documented cultural practices for agricultural production in the region. Farm-scale production costs and revenues associated with the current and alternative best management practices (BMP) were also included in the enterprise budgets. Bundles of BMPs were evaluated at three scenario levels: intensive, typical and minimal implementation of resource saving technologies. Economic simulation analysis was conducted using @Risk software to compare the alternative BMP scenarios and the impact of these scenarios on profitability. The software enabled 500 iterations to be run for each crop and scenario. Preliminary simulation results indicate that minimizing crop inputs was not necessarily the optimal approach for maximizing crop net returns per acre. Implementation of bundles of BMPs can have a positive effect on profitability as well as water quality and quantity.

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Scrutinizing Significance of Trees in Watershed Modeling

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Forests can cover significant portion of watersheds and affect rainfall interception, water losses through evapotranspiration (ET), soil moisture dynamics, surface runoff, aquifer recharge, nutrient leaching, and sediment exports to streams. Despite their critical role in the hydrologic cycle, tree growth is either ignored or superficially considered in hydrological models. We postulate that stand attributes deserve more attention in hydrologic modeling. To that end, this study aims to improve the plant database of a widely applied watershed model, the Soil and Water Assessment Tool (SWAT). To accomplish this goal, we parameterized SWAT with species-specific parameter values derived from publicly available remote-sensing products, field measurements, and literature review. Several studies have identified unrealistic parameter values related to tree growth prediction in SWAT (e.g. BLAI, BIO_E, T_BASE). Although this issue has been somewhat addressed through the calibration of few model parameters and code modifications, to the best of our knowledge, no study carried out a detailed parameterization of trees in SWAT by utilizing observations and/or literature. Here, we applied the SWAT model at multiple scales to simulate leaf area index (LAI), biomass accumulation, and ET of loblolly pine (*Pinus Taeda* L.) and slash pine (*Pinus elliotti*) under varying management, soil, and climate conditions. Tree growth related parameters in SWAT were calibrated at field level for multiple loblolly and slash pine plantations across Alabama, Georgia, and Florida. Model skills in predicting these processes were tested using MODIS LAI and ET derived data, as well as field measured total biomass. Since phenological parameterization is difficult due to lack of observations across large areas (e.g. watersheds), we transferred the improved parameter estimates from the field plots to nearby forested watersheds with observed streamflow data. Models based on improved parameterization and default parameterization were compared to assess the effects of enhanced forest model representation on hydrology and water quality. The utilization of multiple state variables for model calibration (e.g. LAI, ET, and biomass) increases the model robustness and reduces the uncertainties associated with water balance predictions. We conclude that enhanced tree dynamics in watershed models is necessary for increased model reliability in watersheds having significant forest cover.

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Impact of land use change and different management practices on nitrate loading to groundwater in Santa Fe River Basin

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The Santa Fe River basin (SFRB), encompassing 3584 square kilometers in north-central Florida, is dominated by forest and agricultural (primarily corn, peanut, hay, pasture) land uses. The Upper Floridan Aquifer (UFA) is the key water source that supports agricultural production, domestic supply and ecological sustainability in SFRB. In a significant portion of the SFRB, the UFA is unconfined, overlain by sandy soil and associated with high permeable fractured limestones which causes rapid recharge by rainfall and also makes it susceptible to NO_3-N infiltration from various point and non-point sources. Non-point sources such as N fertilizer and organic manure from pastures are of particular concern in SFRB. Basin Management Action Plans (BMAPs) that have been developed to meet the mandated numeric nutrient criterion (NNC) of 0.35 mg/l NO_3-N in springs and rivers in the SFRB estimated that a 35% reduction in NO_3-N leaching to UFA is needed.

A basin scale model was developed and calibrated to predict SFRB river flow and NO_3-N concentrations for the time period 2000-2010 using the USDA Soil and Water Assessment Tool (SWAT). The calibrated model was then used to assess NO_3-N leaching and NO_3-N river concentrations for a range of alternative land use and nutrient and water management practices. Preliminary results show that adoption of reduced nitrogen fertilizer rates and improved irrigation management for existing agricultural land uses and/or conversion from more intensive (row crops, grazed pasture) to less intensive (hay and forest) land uses, can significantly reduce NO_3-N leaching in the SFRB.

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The importance of process representation for simulating coupled surface-groundwater flow: a comparison of SWAT, SWAT-MODFLOW, and DISCO

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We have developed a SWAT-MODFLOW model for the Santa Fe River Basin within the framework of the USDA funded Floridan Aquifer Collaborative Engagement for Sustainability (FACETS) project, which aims to understand land use changes needed to achieve agricultural water security while meeting environmental regulations.

The Soil and Water Assessment Tool (SWAT) is a powerful tool that can simulate the effects of land management practices on water quantity and water quality. Recently, SWAT has been coupled with the USGS groundwater flow model MODFLOW to overcome its limitations with respect to subsurface flow. In the SWAT-MODFLOW model, SWAT handles the surface and soil water component whereas MODFLOW handles the subsurface water component.

To guide our modeling effort we compared our SWAT-MODFLOW model to some other models. Since we have to build a stand-alone SWAT model as a requisite to the SWAT-MODFLOW model, we can compare SWAT and SWAT-MODFLOW and explore if the SWAT-MODFLOW model simulates groundwater contributions to streams more correctly. In addition, we also compared the SWAT-MODFLOW model to a DisCo model in which surface and subsurface flow are coupled fully implicitly and are governed by the diffusive wave equation and the Richards' equation, respectively. While the DisCo model cannot simulate the effects of land management practices as needed for our project, it is a more-physically based flow model than SWAT-MODFLOW. As such, we expect that this model can provide insights into possible limitations of SWAT-MODFLOW. Preliminary results show all models perform reasonably well in terms of simulated stream flows. We discuss the limitations and benefits of the different models. In addition, we illustrate how having multiple models for the same region was beneficial for the development of the SWAT-MODFLOW model.

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The integration of social learning and facilitation methods to enhance stakeholder engagement for the FACETS project

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The Upper Floridan Aquifer (UFA) is a vital resource for those living in Florida, Georgia, and Alabama. Population growth and agricultural intensification are potential threats to UFA water quality and quantity. A complete understanding of ecological and human factors is needed so that intervention does not impair regional lifeways and national food security. The engagement of local stakeholders in scientific efforts can provide information to incentivize wise land use changes.

The Floridan Aquifer Collaborative Engagement for Sustainability (FACETS) project convenes a multi-disciplinary team of scientists to promote economic sustainability of agriculture and silviculture while protecting the ecology and water resources of the Upper Floridan Aquifer. An important aspect of the FACETS project is its focus on stakeholder engagement through a participatory modeling process (PMP). The participants include modelers, agriculture extension specialists, and stakeholders representing key, regional constituents. The PMP works to develop parameters for the modeling platforms and to interpret strategic outputs collaboratively. This work examines the formation and analysis of the PMP through the lens of social learning.

Reed and others (2010) define social learning as, *"a change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks."* Social learning research in FACETS explores the processes in which trust is built among PMP participants. Within participatory modeling research, trust is linked most often to transparent discussions of products, data, and outputs (Falconi and Palmer 2017). Social learning literature argues that social aspects of trust building are of equal importance. Trust comes from having a diverse and knowledgeable learning group and through a facilitated process that can adapt to the shifting needs of the group (DeVente and others 2016, Siddiki and others 2017).

To inform ongoing stakeholder engagement and trust building, FACETS social scientists conducted social learning research and shared findings with the PMP facilitation team. FACETS social learning research is longitudinal. It follows changes in learning and trust in one project over time and takes multiple building blocks of trust into account, including products,

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process, and people. The first phase of research discussed here employed anthropological methods that included both quantitative and qualitative approaches. Quantitative data were gathered at key points along the PMP activities timeline. At the beginning of the process, a baseline survey gathered expectations of stakeholder engagement as well as past experiences with participatory modeling. Surveys at the end of each workshop evaluated the workshop, tracked positive and negative experiences, and compiled any shifts in individual or group perceptions. Qualitative data were gathered through interviews and participant observations during PMP workshops, webinars, other meetings, and during annual interviews with all PMP participants.

Developing a strong community of participants was a key aspect of the PMP design. PMP members were chosen either by an external team of experts or by project team members who were familiar with their work. Georgia and Florida stakeholders came from forestry, conservation, agriculture, and government. PMP project team members represented different FACETS research sub-teams. Workshop structure and activities were crafted carefully to promote interaction among diverse groups and build confidence in PMP membership and project outputs. The project team was transparent about model design and encouraged input. They also devoted time before each stakeholder interaction in preparation meetings to ensure clear communication of complex technical information. In addition to organizing preparation meetings, the facilitation team created a shared language, shifted meeting locations and structure, lengthened workshops, and organized additional webinars with stakeholders to increase information clarity and uptake. The adaptation of the PMP process was informed by social learning findings. For instance, survey responses indicated differing expectations between project team and stakeholders. Although project team members were concerned primarily with addressing project goals, stakeholders were more interested in sharing knowledge and expanding social networks. As determining and addressing participant expectations is a key aspect of community building (DeVente and others 2016, Reed and others 2010), facilitators included activities and unstructured time for networking at all subsequent workshops.

Preliminary findings show an overall high level of confidence in products (results), process, and people (project team and stakeholders). Figure 1 illustrates levels of trust for project team and stakeholders across four variables: 58 percent of stakeholders and 70 percent of the project team reported confidence in the “results presented.” Ninety-two percent of stakeholders were confident and 70 percent of project team members were very confident in the modeling process, credited to direct participation in the project. In both cases, responses as confident (vs. very confident) are attributed to the preliminary nature of data and newness of the process. Seventy-five percent of stakeholders and 70 percent of the project team reported to be very confident in the project team, on account of workshop presentations and past academic achievements. Fifty-eight percent of stakeholders and 40 percent of project team were very confident in stakeholder expertise. Lower confidence in stakeholders compared to project team were attributed to the interpretation that not all stakeholders were versed in modeling before this project began.

These data reveal that the initial community building stage of the PMP has been successful, as the group is developing trust in the products, process, and people. However, we have learned a few lessons. First, maintaining consistent stakeholder membership over a 5-year project is

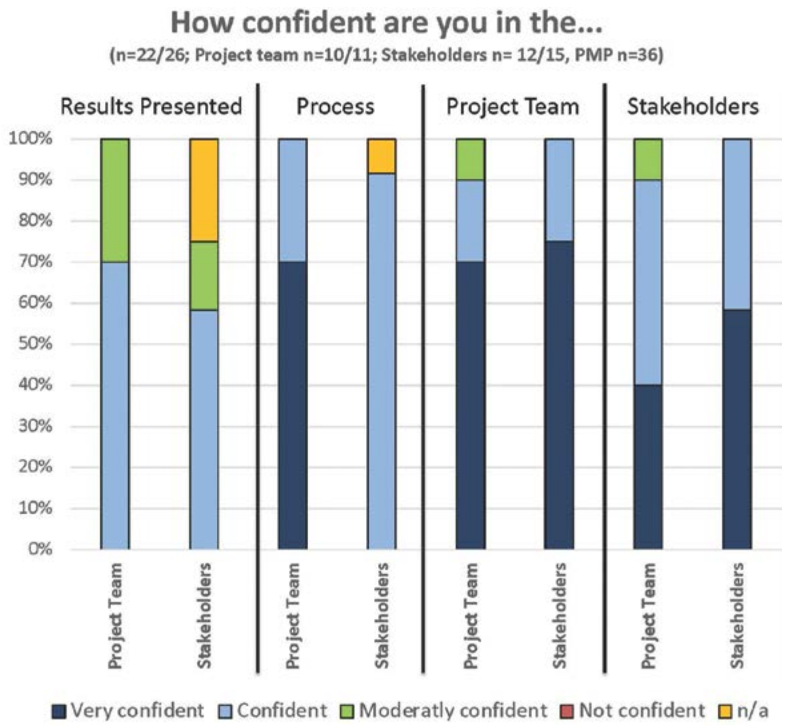

Figure 1—Levels of trust for project team and stakeholders across the four variables.

difficult. Cycling of the PMP was sometimes due to changes in employment (among industry members), while maintaining consistent producer participation has been challenging due to the length and timing of meetings and constant demands of farm management. Second, while beneficial in outcomes, the project team reported that additional meetings to help with community building have been very time consuming in practice. Third, aligning project team and stakeholder expectations creates programmatic challenges for workshop design. The time needed to foster networking for the stakeholders often limits face-to-face group discussions about modeling and associated project outputs. As we are still in the first phase of the FACETS project, we move forward hopeful that we can continue the positive trend and will address present and future lessons through continued social learning research.

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Section 8: Conservation Effects Assessment

Overview of the Impacts of CEAP for the First 15 Years

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In 2003, the USDA Natural Resources Conservation Service partnered with USDA Agricultural Research Service and other agencies to create the Conservations Effects Assessment Project (CEAP) to quantify the environmental effects of conservation practices (CPs) and programs and develop the science base for managing the agricultural landscape for environmental quality. Recently, a CEAP Special issue entitled "Measuring and Understanding the Effects of Conservation within Watersheds" that focuses on the findings of the ARS Benchmark and other watersheds for the first 15 years of CEAP was proposed. An overview of the major findings of the papers in the special issue will be presented. The results of a synthesis of the effects of CPs on soil and water resources at various spatial scales reported in the papers in this special issue and pertinent papers outside the special issue will be presented. Other impacts of CEAP, not related to CPs, will also be presented.

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Comparisons of radar, bubbler, and float water levels in the Goodwater Creek Experimental Watershed

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Abstract—Multiple means of measuring and recording stream stages ensure that a backup is available if the primary equipment fails. Radar-based systems could be a useful primary or secondary measurement device. Evaluations of radar measurement systems exist for lake or ocean tide water levels, but few have been conducted for smaller streams. The study compares water levels measured in the 72-km^2 Goodwater Creek Experimental Watershed with a radar, a flow bubbler, and a float-driven sensor. Diurnal variations caused by solar radiation on the radar unit were eliminated by insulation. At high stages, the float and chart system produced an oscillating pattern with magnitude increasing proportionally to the stage. The differences between radar and bubbler values were also proportional to stage. The relationships between stage and oscillation magnitude, and between stage and difference between radar and bubbler values could provide an automated method to quantify the uncertainty of stage measurements.

INTRODUCTION

The height of the water surface of a flowing stream or river above an arbitrary datum is a common measurement from which one can derive discharge. The instantaneous value of the stage can be directly read on a staff or other type gage (Sauer and Turnipseed 2010). It can also be recorded via an automated sensing mechanism that uses floats, pressure transducers, or acoustic methods (Sauer 2002). Automated systems allow continuous monitoring of stage, which enables the recording of event dynamics when observers cannot be present. All automated systems include a sensor and a recorder. The most common ones include the float and chart systems connected to a chart, and the bubbler systems connected to a datalogger. Submersible pressure transducers can also measure stage but are less used in streams because they incur damage when left in freezing water.

Early automated systems consisted of a float in a stilling well connected via a pipe to the middle of the stream channel. A stylus connected to the float traced the water level variations on a chart placed on a rotating drum. Hydrologists read the chart by recording the points (time and stage) where there was a change in the slope of the line, which indicated a change in the rate at which the stage was increasing or decreasing. Reading the chart was tedious and resulted in breakpoint data, i.e., data points at irregular intervals.

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In bubbler systems, a gas bubble is pushed out of an orifice placed in the stream or a stilling well. An internal pressure transducer produces an output voltage that is proportional to the pressure needed to push this bubble out of the orifice, which is proportional to the height of water above the orifice. The datalogger records this pressure and converts it into a stage value. The combination of a float and chart system and a bubbler system provides a reliable means of measuring stage, which requires reading charts only when the bubbler or electronic recording of data fails to function.

More recent techniques for water level measurement avoid any contact between the sensor and the water. They rely on acoustic, radar, and optical measurement methods. A radar measurement system emits a radio wave of known frequency and captures the radio wave reflected by the water surface. It then analyzes the phase shift between the emitted and reflected signals (frequency modulated continuous wave [FMCW] radar) or the transit time of the signal (pulse radar).

Each of these techniques has advantages and shortcomings. Bubblers generally require the installation and maintenance of a stilling well and maintenance of the line that goes to the middle of the channel. Noncontact systems such as radars eliminate the need for a stilling well; the water surface height is measured directly in the stream. These systems reduce the risks of losing the sensor during a large storm and are generally simpler to operate. However, they are sensitive to debris floating on the water surface and can be affected by wind and waves (Fulford and others 2007, Sauer and Turnipseed 2010).

Radar measurement methods have been tested extensively for tide (Míguez and others 2008, Woodworth and Smith 2003) and lake or reservoir levels (Fulford 2016, Fulford and Davies 2005, Fulford and others 2007). Radar evaluations for tide level measurements (Míguez and others 2008, Woodworth and Smith 2003) showed that they functioned as well as bubblers. Fulford and Davies (2005) showed that the theoretical measurement uncertainties of lake level measurements were larger with a radar system than with a float and chart system. Compared with those from a bubbler, the radar uncertainties were larger at low stage but smaller at high stage. Field and laboratory testing of radars and float and chart systems showed that radar measurements may have a small negative bias and may be affected by a range of issues including reflection of the radar beam from a bridge pier, diurnal cycling caused by excessive heat on the radar case or thermal expansion of bridge spans, jumps of water readings suspected to be caused by wind or waves, and debris or ice on the water surface (Fulford 2016, Fulford and others 2007).

None of these evaluations allowed the objective determination of the “most valid” response because there were never more than two sensors. Having more than two sensors provides the means to further decrease the uncertainty of the measurement. If two or more sensors give similar values, it is more likely that this value is the correct one. If one sensor gives a value greater or lower than two or more sensors, the likelihood that this sensor is failing is greater. There is a need for evaluating radar measurement against more than one other sensor.

There is also a need to quantify the uncertainty of each discharge data point separately because uncertainties are not the same at low and high stage. Uncertainty quantification will provide modelers more insight into the data they use for model calibration and validation, and ultimately for comparing the discharge and water quality effects of watershed management strategies, including land use management and conservation practice implementation. For water quality assessment, uncertainties in discharge values need to be combined with uncertainties caused by the water quality assessment to arrive at the uncertainty of the water quality constituent transport. For those effects to be significant, they need to be greater than the uncertainties inherent in measurements and model simulations.

Therefore, the objectives of this study were to: 1) evaluate radar measurements for their robustness, measurement uncertainty, and accuracy in comparison with two other sensors, and 2) quantify the uncertainty of stage measurements and derive the uncertainty of discharge estimates.

METHODS

Site Description

The measurement site is located at the outlet of the 72-km^2 Goodwater Creek Experimental Watershed (GCEW), in northeast Missouri. The GCEW is a headwater watershed in the 6400-km^2 Salt River Basin, which drains to Mark Twain Lake. Stage and discharge monitoring at this site started in 1972 (Baffaut and others 2015), after construction of a V-notch weir. The site is now part of the infrastructure of the Central Mississippi River Basin site of the Long-Term Agroecosystem Research (LTAR) Network (Sadler and others 2015). Baffaut and others (2015) describe the history of stage measurement at this site and current monitoring equipment and data collection up to 2015. Briefly, monitoring started with two Belfort FW-1 chart recorders connected to a float in a stilling well, one with a daily clock and the other with a weekly clock for backup purposes. In 2003, a flow bubbler was installed as the main measurement device and the weekly recorder was kept as backup. The current bubbler model is the 4230 ISCO (Teledyne ISCO, Inc., Lincoln, NE) and collects stage data every 5 minutes. The stilling well and the bubbler lines are heated to prevent ice accumulation in the well and damage to the bubbler line.

A radar (Campbell® CS476-L, Campbell Scientific, Inc., Logan, UT) was added to the infrastructure in late 2018 as an alternative system to the float and chart system. Our strategy was to evaluate the radar system while the chart system was still in place in order to have measurements from the three systems (radar, bubbler, and float and chart) at the same time. Five-minute radar and bubbler measurements are sent by telemetry. A technician reviews stage records on a daily basis to identify potential need for a maintenance operation. In addition, that same technician conducts weekly maintenance visits, including weekly chart retrieval and replacement. The technician also visits the site after each major runoff event to collect water samples and makes sure everything is fine. After a few months to understand the operation of the radar, we collected stage data using the three measurement devices from May 13, 2019 until August 31, 2020 and evaluated the three systems for their robustness and accuracy.

Robustness Evaluation

Robustness evaluation included regular maintenance and calibration requirements. In addition, we evaluated how common conditions that disturb stage measurement can be detected with each measurement system: logjams, ice conditions, and spikes.

Logjams occur when one large log gets wedged in front of, in, or immediately beyond the weir. Additional logs and other debris can then be trapped on top of that one creating a logjam. Depending on flow conditions and the size of the logjam, this may affect the stage. The maintenance visits certainly prevent these jams from being undetected for more than a week, but stage records sometimes can indicate that something is amiss.

Ice conditions occur when the water surface or the whole water column freezes. If cold weather lasts, ice conditions can result in an ice jam: an accumulation of ice blocks over the weir and no stream discharge. With less cold temperatures, the water surface may be covered with ice with flowing water underneath.

Spikes occur when stage appears to increase or decrease suddenly and then returns to its previous value within one or two time steps. In this watershed, such spikes do not occur naturally and are not seen on the paper charts but do occur with bubblers, especially when one conducts a line purge (about a once-a-month occurrence at this site).

Measurement Assessment

Theoretical measurement uncertainty— The theoretical total uncertainty of a measurement combines systematic and random errors by taking the square root of the sum of squared errors. In this study, we combined errors defined in equipment specifications, those derived from information about each instrument in previous studies, and personal experience. For the radar, manufacturer specifications about measurement accuracy and resolution (the smallest change that can be measured) and the calibration uncertainty (uncertainty of the physical measurement used to calibrate the radar level, assumed to be 0.01 foot) defined the overall measurement uncertainty. Manufacturer specifications were also used to estimate the bubbler measurement uncertainty. Specifications included the measurement accuracy, maximum error associated with a temperature deviation from the 72 °F calibration temperature (assumed to be 36 °F for this calculation), the long-term calibration change (0.5 percent of reading), the drift correction, and the calibration uncertainty. For the float and chart system, we considered the maximum float-lag error, the line shift error for a maximum change of stage of 1 foot (which is unlikely to be exceeded over a 5-minute interval), and the counterweight submergence after Rantz (1982), and added the random chart reading error and the calibration uncertainty. Since stage measurement uncertainty varies with stage, we estimated it for two values near either end of the peak stage range: 2 feet and 10 feet.

Discrepancies between measurements— Differences of more than 0.01 foot between the bubbler and radar were identified for base flow and high flow conditions separately (defined by stage lower or greater than 1 foot). Periods with differences greater than 0.01 foot were investigated visually to identify what may have caused the discrepancy: icy conditions, logjams, spikes, or another unexpected reason. Logjams and icy conditions were easily detected by large differences between the radar and bubbler combined with a chaotic radar signal. Air temperatures monitored at a nearby site and knowledge of the conditions at the site (informed by a written note log from the technician) confirmed what had happened. If a reason was identified, the faulty record was removed and the remaining measurement was considered the correct one. After several months, visualization of the differences during base flow conditions showed that solar radiation (time of the day) affected the radar measurements. Following insulation of the box that contained the radar unit on August 6, differences during base and high flow conditions were analyzed for a whole year, from August 7, 2019 to August 6, 2020.

Analysis of discrepancies during high stage conditions was limited to the period after insulation, i.e., from August 7, 2019 to August 6, 2020. To limit our readings of the charts to short periods, we restricted our analysis to peak stage values. For each storm event, we compared the radar, bubbler, and chart readings for a 3 to 6 hour period around the peak stage, which corresponds to the period with the largest oscillations on the chart. Linear relationships were determined between the magnitude of the oscillations during the peak period of an event, the maximum difference between bubbler and radar stage during that period, and the peak stage value.

Discharge Calculation

Stage data correction—The comparison of bubbler, radar, and chart stages did not allow a determination of which measurement was the most accurate (see results in next section). Therefore, the previously determined relationships were used to derive a final stage value and its associated uncertainty:

- If the bubbler and radar values were present and not affected by ice, logjams, or spikes, we used the average between the radar and bubbler stage values and assigned half of the difference between the two values to the stage uncertainty.
- If the bubbler value was missing because of a spike, we interpolated the missing values and proceeded as above. If the radar value was missing or affected by floating debris, we used the bubbler value (this was done for 6,719 out of 108,858 values, or 6.17 percent). In this case, we estimated the difference between radar and bubbler measurements as a function of stage and assigned this value to the uncertainty of the data point.

Quantification of discharge uncertainty—Once stage was determined, the existing rating curve was applied to the mean, upper, and lower values of stage to determine the mean, upper, and lower values of discharge. The uncertainty in annual flow resulting from stage reading uncertainty was determined.

RESULTS AND DISCUSSION

Robustness

Maintenance and calibration requirements—The float and chart system is free of calibration. Weekly field visits ensure that the mechanism is working properly and that ink is plentiful. Given our equipment setup, one needs to replace the chart paper each week. However, diminishing availability of supplies, such as chart paper, for this type of system makes the cost more expensive. In addition, the reading of the charts is time consuming, not always consistent between readers, and subject to human errors.

The bubbler system requires regular maintenance to ensure that the line is not affected by debris and that gas pressure is appropriate. From time to time, purging of the line is necessary, especially after large events that transport large quantities of sediment. The connection of the bubbler to a datalogger and telemetry system ensures daily readings that alert technicians of a problem with the equipment.

The radar requires very little maintenance. Calibration is required upon installation and needs to be checked from time to time. Simultaneous visualization of the radar and bubbler stage traces made departures from correct calibration easier to identify, both for the bubbler and for the radar. Initial measurements showed that solar radiation on the radar unit affected the measurement significantly. Covering the box with insulating foam resolved the problem.

Ice and logjam conditions—Debris floating on the water create a noticeably different stage trace with a radar device. Debris cause the stage trace from the radar to be erratic, while traces from the bubbler or the float and recorder remain smooth because they measure water level in the stilling well. However, backwater effects caused by these debris can affect stage, and discharge, even if the trace from the bubbler does not indicate any problem. Again, simultaneous visualization of the bubbler and radar stages provides a means to identify ice or logjams. For each of these ice- and logjam-affected periods, the radar measurements were deleted and replaced by the bubbler measurements.

Spikes—When spikes occur, one needs to detect and remove them. Analysis of the radar and bubbler stages allowed easy detection of these spikes: a very short period (two to three time steps) during which the difference between the bubbler and the radar was greater than 0.01 foot.

Measurement Assessment

Theoretical measurement uncertainty— Tables 1–3 showing overall theoretical uncertainties indicate that the radar system had the potential to provide a measurement with less uncertainty than the float and chart system, or the bubbler. Specifications implied an accuracy of 0.014 foot, or 0.7 percent at 2 feet of stage, and 0.1 percent of the reading at 10 feet. As expected, relative uncertainties were greater for lower stage values.

Table 1—Uncertainties caused by each source of error and overall measurement uncertainty for the radar

Stage	Accuracy error	Resolution error	Calibration uncertainty	Overall uncertainty	Relative uncertainty
- - - -	- - - -	- - - -	*feet*	- - - -	*percent*
10.0	0.010	0.003	0.010	0.014	0.1
2.0	0.010	0.003	0.010	0.014	0.7

Table 2—Uncertainties caused by each source of error and overall measurement uncertainty for the bubbler

Stage	Measurement error	Temperature effect error	Drift correction	Long-term calibration change	Calibration uncertainty	Overall uncertainty	Relative uncertainty
- - - -	- - - -	- - - -	*feet*	- - - -	- - - -	- - - -	*percent*
10.0	0.005	0.059	0.002	0.050	0.010	0.078	0.8
2.0	0.005	0.011	0.002	0.010	0.010	0.018	0.9

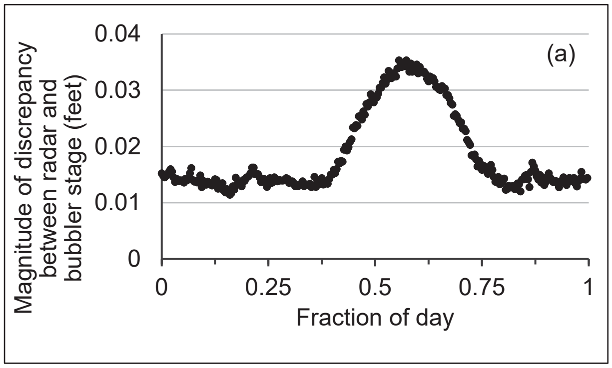
Table 3—Uncertainties caused by each source of error and overall measurement uncertainty for the float and chart

Stage	Maximum float-lag error	Line shift error	Submergence of counterweight error	Calibration uncertainty	Chart reading error	Overall uncertainty	Relative uncertainty
			feet				*percent*
10.0	0.018	0.001	0.010	0.010	0.005	0.023	0.2
2.0	0.018	0.001	0.010	0.010	0.005	0.023	1.2

Rantz (1982) listed uncertainties associated with the float and chart system as a function of the diameter of the float, and the material of the counterweight and float tape. For a 6-inch-diameter float and a 1.25-pound stainless steel counterweight and stainless steel float tape, these errors combined with the random reading error and the calibration uncertainty amounted to 0.023 foot, which was 0.2 percent of reading at 10 feet and 1.2 percent at 2 feet.

Based on manufacturer specifications, the measurements with the bubbler system had the largest uncertainty, which was contributed by the maximum measurement error, the temperature-induced error, the long-term calibration change, and the calibration uncertainty. These resulted in overall errors up to 0.078 foot for a 10-feet stage and 0.018 foot for a 2-feet stage. These results indicate that the radar should be the primary sensor. In that case, a solid backup would be needed to address the times where ice or logjams prevent accurate reading of the water surface. Selection of the float and chart system as the secondary device would be logical based on theoretical uncertainties. However, the required human intervention to collect, replace, and read the chart, and diminishing availability of chart paper, are disincentives to that option.

Discrepancy between measurements—For base flow conditions, a few months of data suggested that the readings were affected by solar radiation and the associated heat. We therefore insulated the box containing the radar with Styrofoam, which appeared to solve the problem. Figure 1a shows the average magnitude of discrepancy as a function of the time of day (a surrogate for solar radiation), which increases as solar radiation increases. Insulation of the



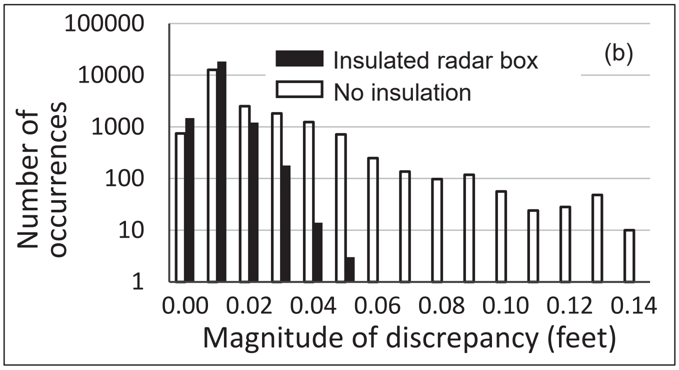


Figure 1—Discrepancies between radar and bubbler readings at low flow conditions during 86 days without insulation: (a) average magnitude of discrepancy versus fraction of day, and (b) frequency of discrepancies compared to those observed after insulation of the radar housing box.

radar housing box resolved that problem. The number of discrepancies greater than 0.04 foot became negligible during the 86 days following insulation of the radar box, and the frequency of those greater than 0.01 foot was reduced by 28 percent compared to the 86 days of operation without any insulation (fig. 1b). After insulation, 6.6 percent of the base flow measurements showed discrepancies greater than 0.01 foot.

Twenty-five events were recorded between August 12, 2019 and August 11, 2020, reaching peak stage values from 2.1 to 8.3 feet. For each of these events, small oscillations of the water surface during the peak period of the event caused the width of the pen trace to increase. The oscillations were visible on the chart (fig. 2a) but not in the bubbler or the radar signals (fig. 2b) because the flow bubbler and the radar average values over the 5-minute reporting period. Such oscillations of the water surface are believable based on photos taken during large events. The thickness of the line gradually increased and then decreased during the peak period. Over the period of study, the maximum thickness varied from 0.02 to 0.1 foot and was proportional to stage (fig. 3a).

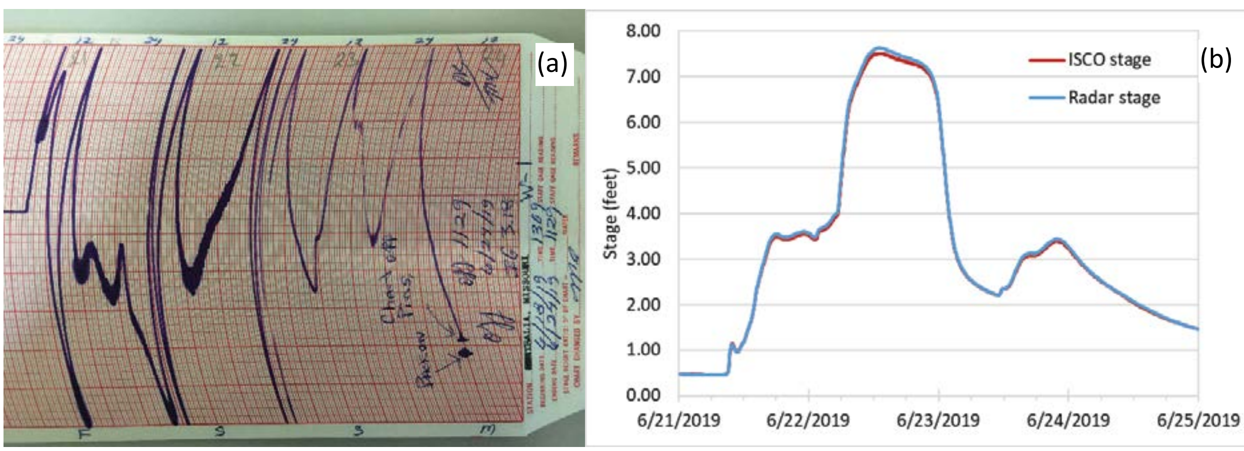


Figure 2—Paper chart (a) and radar and ISCO (bubbler) signals (b) from June 21–24, 2019. The width of the paper chart corresponds to a 1-foot rise or fall. When the pen reaches the top or the bottom of the chart, it reverses its direction of increase or decrease and continues recording.

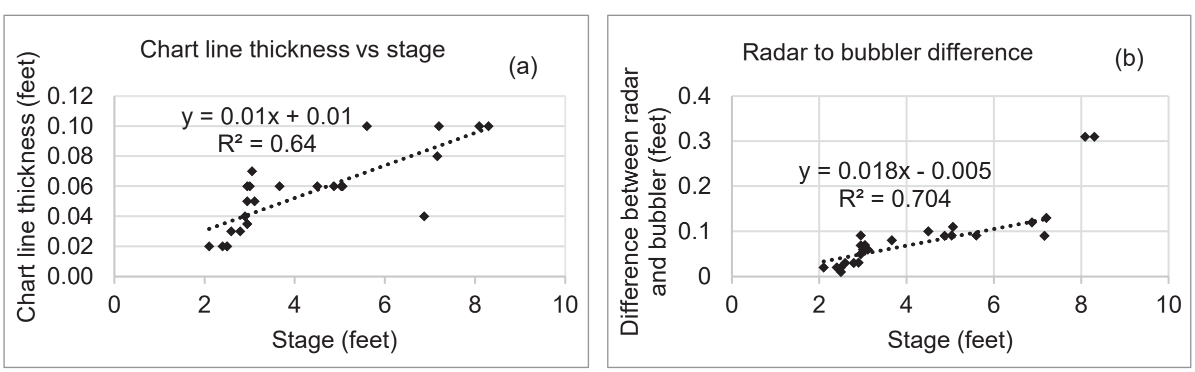


Figure 3—Maximum pen trace thickness (a) and difference between radar and bubbler (b) as a function of peak stage. Observations with stage greater than 8 feet were excluded from regression fit.

Radar level was always greater than the bubbler level during event peaks. Multiple causes may explain these differences, including a difference of level between the center of the stream and the stilling well, or the fact that the top of the oscillations dominate the radar measurement. As for the magnitude of the oscillations visible on the chart, the differences between the radar and bubbler readings during the peak period of each event were proportional to stage (fig. 3b) up to 7.5 feet. Two points at peak stage of 8 feet stand alone, and more data points with peak stage between 7.5 and 8.5 feet are needed to assess the nature of the relationship in that range.

Quantification of Discharge Uncertainty

The overall uncertainty in annual flow discharge caused by stage measurement for the year from August 2019 to August 2020 was 3 percent. This uncertainty is slightly greater than the range of discharge uncertainties associated with stage measurement in streams and rivers, which Harmel and others (2006) reported as 1–2 percent. However, the range of discharge uncertainty varied with stage, ranging from 0–44 percent at stages less than 1 foot to 0–18 percent between 1 and 6 feet, 0–17 percent between 6 and 8 feet, and 12–19 percent above 8 feet (fig. 4). These uncertainties are in addition to other sources of uncertainty, such as uncertainty of the rating curve and uncertainty of flow measurements performed to build the rating curve. Note that for this gaging station, the uncertainties of the rating curve and its associated flow measurements start to increase faster once stages are greater than 6 feet (Baffaut and others 2014), which marks the upper bank elevation. During events with stages greater than 6 feet, the flow spills into the flood plain, which complicates flow measurement.

CONCLUSIONS

In this study, we assessed stage measurement uncertainty obtained with a float and chart system, a flow bubbler, and a radar measurement device. Theoretical uncertainties of each measurement favor the use of a radar system as the primary sensor. Maintenance and chart reading requirements and diminishing availability of chart paper tend to favor the bubbler system as the secondary system, despite lower errors obtained with the float and chart system.

Solar radiation and heat on the radar unit caused large discrepancies between radar measurements and measurements

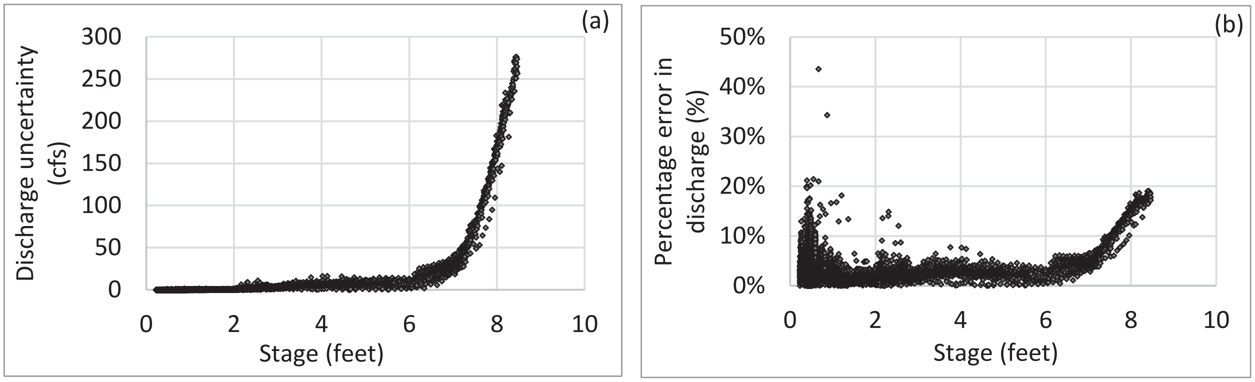


Figure 4—Discharge uncertainty caused by stage measurement errors as a function of stage: (a) absolute uncertainty and (b) relative uncertainty.

made with the bubbler system. These discrepancies were reduced to the same magnitude as other sources of uncertainty once the box that contained the radar unit was insulated. Analysis of errors obtained with each system showed that these errors increased with stage, especially once stage reached 6 feet, which is the bank elevation of this midsize watershed stream. Oscillations of the water surface visible on the chart were of a magnitude proportional to the difference between the radar and the bubbler measurements. Therefore, the difference between radar and bubbler was used as an estimate of the measurement error. If either the radar or bubbler measurement was not available, the relationship between the bubbler to radar measurement difference and the stage was used to estimate the difference and the uncertainty of the measurement.

Given these assumptions, the total uncertainty caused by stage measurement for the total amount of water that flowed from August 7, 2019 to August 6, 2020 was 3 percent of the total annual amount. However, it ranged from 0 to 20 percent, depending on the stage. The uncertainty estimation method can be used moving forward to associate a measurement uncertainty to each stage value and derive the corresponding discharge uncertainty caused by stage measurement errors. This uncertainty will have to be combined with uncertainties caused by the rating curve and the flow measurements used to build and adjust the rating curve to arrive at a total discharge uncertainty. Going backward, the proposed method can be used to retroactively associate uncertainty values to past measurements.

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Agricultural producers' willingness to accept payments for improving water resources in the Florida Aquifer

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Increased adoption of best management practices (BMPs) by agricultural producers is a potential tool for improving water resource conditions. However, the economic feasibility of this approach is largely unknown in watersheds connected to the Florida aquifer. This study assessed the farm and forest-level economic tradeoffs associated with a suite of proposed BMPs for typical agricultural enterprises and crop rotation in S. Georgia and N. Florida (row crops, planted pines, and hay). We then surveyed producers to determine what level of incentive payments would be required to ensure their participation in voluntary BMPs, which often require high start-up and/or installation costs and can affect farm and forest yields. The survey included economic valuation questions designed to understand producer preferences in an elicitation format known as Best-Worst Choice modeling. Results of the survey are used to estimate a supply curve for water resource improvements from producers as a function of price, and in the context of a hypothetical payments program, can predict levels of producer participation and the subsequent changes in water resource conditions in the study area.

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Ecological Effects of Agriculturally-Sourced Colored Dissolved Organic Matter in Two Mississippi Watersheds

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Colored dissolved organic matter (CDOM) can be a significant component of water quality that is often overlooked, especially in agricultural landscapes where eutrophication and erosion are viewed as the most pernicious sources of water quality impairment. Influxes of agriculturally-sourced CDOM typically occur during large storm events coinciding with crop drying prior to harvest (crop-sourced CDOM) and/or with top soil erosion after harvest and tillage (erosion-sourced CDOM). In the current study, surface water quality of two agricultural watersheds in western Mississippi, Beasley Lake and Roundaway Lake, were monitored from 2017-2019 and included suspended solids, nutrients, CDOM, algae and dissolved oxygen. Crop-sourced CDOM influxes occurred in Roundaway Lake during August 2017 and September 2018 producing hypoxic conditions (dissolved oxygen < 2 mg/L) in an upstream reach, lasting days to weeks and coinciding with inhibition of algal photosynthesis. Erosion-sourced CDOM occurred every year of monitoring in both watersheds, strongly correlating with total suspended solids ($r > 0.70$). Using classification and regression tree (CART) analyses, erosion-sourced CDOM in Beasley Lake significantly influenced algal biomass and photosynthesis in conjunction with nutrients and seasonality. By comparison, both crop-sourced CDOM and erosion-sourced CDOM in Roundaway Lake influenced algal biomass and photosynthesis in conjunction with nutrients and seasonality. In general, more terrestrial-derived CDOM with greater molecular weight and increased color decreased algal biomass and inhibited algal photosynthesis in both watersheds. Study results indicate that reduction of both nutrients and inputs of colored dissolved organic matter into agricultural water bodies is necessary to help mitigate hypoxia and stabilize primary productivity in agricultural watersheds.

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A Novel Transient Tracer for Assessing Watershed Lag Time and Agricultural Nitrogen Fate

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Groundwater transit time measurement is important for understanding the time span required for conservation practices applied to agricultural landscapes to influence the stream water chemistry in watersheds. Standard measurement methods of water lag time are limited to groundwater because of the volatile nature of the transit tracers commonly employed. We recently discovered a non-volatile tracer that can accurately quantify stream water at an outlet and greatly decrease the uncertainties associated with translation of measurements into estimates of watershed lag time. This advancement was the result of a fortuitous reformulation of the commonly-used herbicide metolachlor from racemic to the S-chiral form in 1999 to increase product herbicidal activity. Metolachlor is metabolized to metolachlor ethane sulfonic acid (MESA), and the parent chirality is retained. MESA is very stable and highly soluble in soil and aquifer sediment and therefore acts as a conserved transport analog of agricultural nitrate. The chiral ratio of MESA in a water sample is measured, and using a two end-member model, allows for calculating the MESA pool into pre- and post-1999 formulation components. Application of a suitable transit model permits estimates of water transit age as well as age of associated nitrate. Chiral MESA analyses of water samples collected in the Choptank River watershed over the period from 2005 to 2019 demonstrated the utility of chiral MESA to fractionate nitrate into two age pools because of strong correspondence between the chiral signal and observed stream nitrate dynamics. This methodology will provide watershed transit times useful for assessing effectiveness of conservation practices on surface water chemistry and watershed export of agricultural contaminants.

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Advancing Conservation Effects Assessment in Watersheds: Delivering Outcomes for the Farm Bill

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There are many expectations in the recent Farm Bill regarding outcomes of conservation, for watersheds, water quality, water scarcity as well as other resource concerns addressed by USDA Conservation Programs. Efforts to assess conservation effects in watersheds and on water resources need to produce credible data. They need to be conducted over the long-term, yet expectations dictate they also need to provide timely results to be applied to adaptive management of agricultural systems. Assessments should be used to build more resilient agriculture, in the face of extreme events. Assessments should inform watershed and conservation planning at local levels, and at the same time, outcomes should inform program design and delivery approaches at larger scales. How can this broad range of expectations across spatial and temporal scales be best addressed going forward with science, assessment and data analysis efforts to yield credible results to support agency mandates? What additional capacity is needed to better accomplish this, building on existing efforts, while advancing our ability to speak to outcomes of conservation efforts and advancing our capacity for enhanced planning and more effective watershed efforts?

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Section 9: Coastal Plain Watersheds

Putting the Research Catchments on a Map: An Overview of Research Sites that have Shaped Knowledge in Trans-Disciplinary Research

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Long-term catchment studies have profoundly influenced science, policy, management, education, and public perception of natural resources around the world. Despite the legacy, some catchment studies have been decommissioned, while others face uncertain futures. In an environment of change, we need them more than ever. This represents a collaborative effort to promote the catchment studies, and to highlight the potential for global watershed research through comparison of data from long-term, place-based research watersheds. To that end, we provide this map showing locations of research catchments from around the globe, including those featured here at the Seventh ICRW, in hopes it will stimulate discussion about the state of catchment sciences and the sites that make the science possible. We encourage the ICRW participants to add other research watersheds to the map that are not yet represented. Over the coming year the project leaders will begin to reach out to all participants regarding opportunities to collaborate in the creation of a virtual network of watershed science.

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Little River Experimental Watershed history

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Long-term, watershed-scale hydrologic and climatic data are invaluable for natural resource and environmental planning and management. Historically, long-term hydrologic records have proved critical for flood forecasting, water conservation and management, agricultural and drought planning, and addressing critical environmental and water quality issues. Establishment of the Little River Experimental Watershed (LREW) (Bosch and others 2007) resulted from concern generated by the Dust Bowl, a drought that occurred in the United States in the 1930s. This drought stimulated the U.S. Senate to establish a network of watersheds that would provide a better understanding of linkages between rainfall, land-management, and watershed streamflow, particularly as it concerned agricultural regions. The result was Senate Document 59 (U.S. Senate 1959) which authorized the U.S. Department of Agriculture Agricultural Research Service (ARS) to established regional watershed hydrology research centers across the Nation in the 1960s, one of which became the LREW. The ARS's Southeast Watershed Research Laboratory (SEWRL) was subsequently authorized by Congress in October of 1965. The primary intent of the LREW site was to develop an improved understanding of basic hydrologic and water quality processes on Coastal Plain watersheds and to evaluate the effects of agricultural management practices on the region's natural resources and environment.

Initial work focused on site selection, with collaborative studies between the SEWRL and the University of Georgia (UGA) on regional geology, soils, topography, hydrography, and weir design. Theoretical and scale weir design studies were conducted both at UGA and ARS Hydrology Lab in Stillwater, OK. In January of 1966, the Laboratory selected the Little River Watershed near Tifton, GA. Key features included:

- An aquiclude separating surficial and regional aquifers, convenient for water balance studies since it could be used to measure baseflow component
- A low-gradient watershed with large floodplains which was representative of other watersheds in the region
- A watershed which includes dense riparian buffers

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- Located within an important agricultural region, with associated research facilities
- Located in the headwaters of the Suwannee River Basin, a major interstate basin of the United States

Once the watershed was identified, plans and arrangements were developed to install weirs at several road crossings, selecting paired and nested subwatersheds that could be compared for data analysis. The original design identified 16 possible measurement locations. In addition, sites were identified for collecting complimentary rainfall data. Ultimately, 7 weir installations and 55 rainfall collection stations were installed. From 1967 to 1972, seven weir installations were constructed at an estimated cost at that time of $1 million dollars, measuring watersheds ranging from 3 km^2 to 334 km^2. Key installation features included:

- Virginia V-notch weirs
- Steel pilings driven to the aquiclude across the stream and along the side walls
- Weir caps designed for free overflow
- Upstream and downstream measurement of water level for interpretation of flow rates and submergence
- Upstream catwalks for stream rating

Over the history of the watershed program, additional weir and rainfall stations have been installed over various periods of time. There are currently 9 weir installations and 41 climate and rainfall stations (fig. 1).

Long-term (up to 51 years), research-quality streamflow data have been collected for up to nine flow measurement sites. During the history of the Laboratory, > 1000 journal articles have been published by SEWRL scientists. Some of the major products resulting from the LREW research include:

- Characterization of the hydrology and evapotranspiration of the watershed, resulting in publications on water balance, extreme events (peaks and droughts), and baseflow
- Publications characterizing riparian buffer system (a key feature of the watershed) impacts on water quality, evapotranspiration, and hydrologic patterns
- Impacts of land-use changes, primarily having to do with conversion from forest to row-crop and vice versa
- Trends in water quality
- Remote sensing, primarily on crop assessment and soil water conditions

The LREW continues to play an important role in national and international watershed research programs. The high quality, reliable long-term hydrologic and climatic data that have been collected have proved invaluable to many research efforts. Currently we are heavily involved in the Conservation Effects Assessment Project in partnership with the Natural Resources Conservation Service, the ARS Long Term Agroecosystem Research program, natural resource modeling, and biofuel research as part of the U.S. Department of Agriculture Southeast Biomass Research Center.

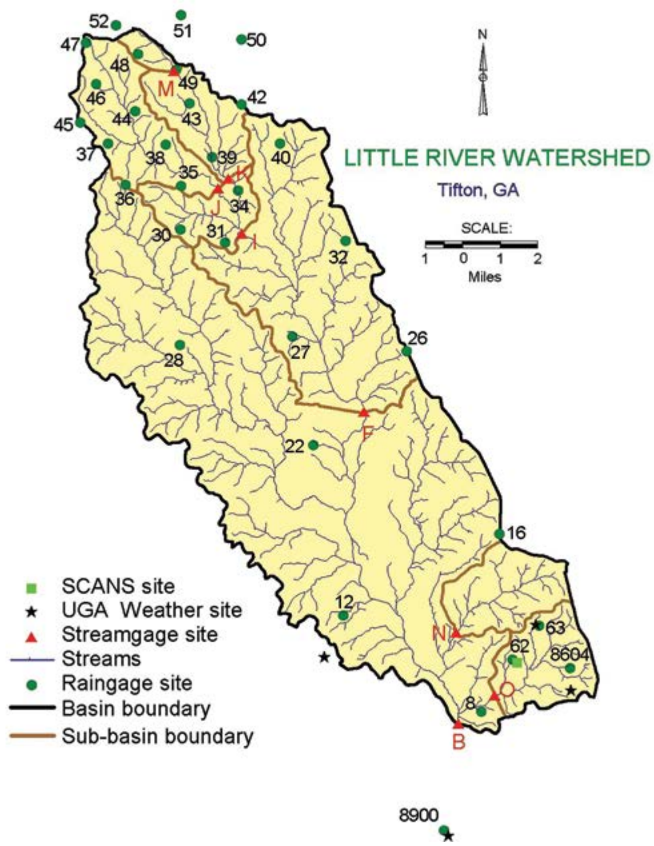

Figure 1—Current configuration of the Little River Experimental Watershed. Note: UGA = University of Georgia, SCANS = NRCS Soil Climate Analysis Network.

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Peak flow characterization for the Little River Experimental Watershed

David D. Bosch, Katrin Bieger, Jeff G. Arnold, and Peter M. Allen

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Peak-streamflow estimates are required for assessment of flood risk, flood-plain management, and cost-effective design of structures. A lack of understanding of peak-streamflow responses of watersheds can lead to extreme economic impact and in some cases loss of life. In watersheds with shallow water tables, peak streamflow is heavily influenced by available water storage in the subsoil. Available storage is influenced by topography, geology, vegetation, antecedent rainfall, and climatic season. Accurate streamflow estimates must incorporate accurate representations of the available storage.

We examined 48 (1972–2019) years of streamflow data from the Little River Experimental Watershed (LREW) to determine peak flow characteristics and relationships to antecedent moisture conditions. The LREW is located near Tifton, GA, in the U.S. Coastal Plain physiographic region. From 1967 to 1972, seven weir installations were constructed in the watershed to measure watersheds ranging from 3 km^2 to 334 km^2 (Bosch and others 2007). Data from only the largest measurement station, Station B, were used for this analysis. The watershed has mixed land use, with 48 percent of the area used for agricultural production and 39 percent forested. The Hawthorne geologic formation is a dominant feature in the watershed and one that controls flow processes. This geologic formation forms an aquiclude between the surface and subsurface aquifers and supports the surficial aquifer system which generates 53 percent of the watershed streamflow via baseflow. The surficial aquifer fills during late winter and spring months and dries throughout the summer due to climatic patterns. Flow within the watershed is heavily influenced by saturation in the surficial aquifer. Peak flow events from this period of record were examined based upon antecedent rainfall, aquifer saturation, and climatic season. For this analysis, we (1) extracted all annual maximum flows from 1972 to 2019, (2) determined probability distributions of peak flows, (3) determined return periods, and (4) examined seasonality and distribution.

Seventy-five percent of all daily peak flows during the record period were found to occur during the months from January through April. Ninety-eight percent of the observed annual peak flows were < 140 cms, with only 2 percent of the observed annual peak flows exceeding this rate. Comparisons of peak flow return periods for the Little River Station B were found to yield lower peak flows for equivalent return periods than those typically used for the region (fig. 1).

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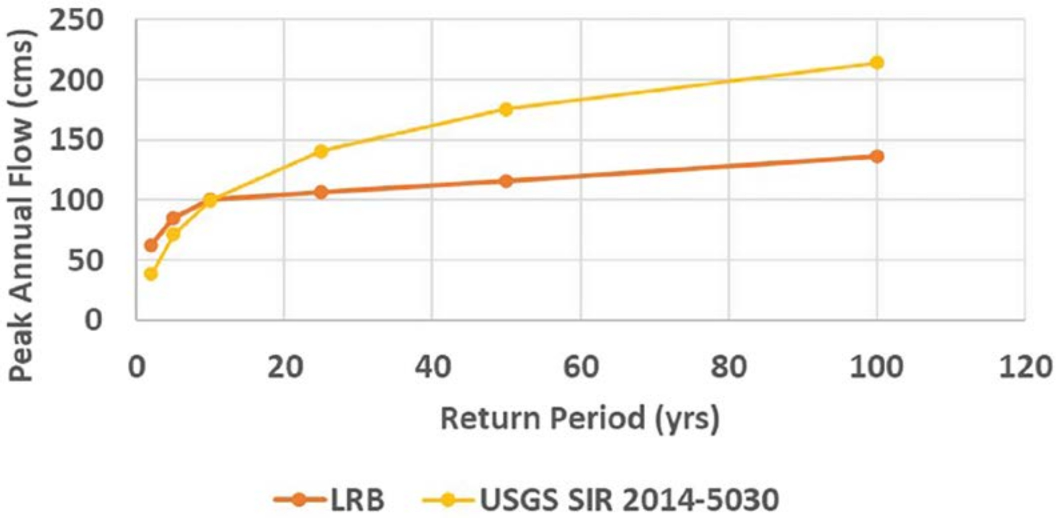

Figure 1—Comparison between peak flow return periods for the Little River Watershed Station B (LRB) and predictions from the U.S. Geological Survey Scientific Investigations Report 2014-5030 (USGS 2014).

The primary findings from the analysis were: (1) the majority of the extreme events occur from January through April; (2) extreme events are heavily influenced by rainfall intensity, not just volume; (3) observed annual maximum flows are less than standard predictions; and (4) maximum flows are heavily influenced by available storage.

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Bosch, D.D.; Sheridan, J.M.; Lowrance, R.R. [and others]. 2007. Little River Experimental Watershed database. Water Resources Research. 43(9). W09470. doi:10.1029/2006WR005844.

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A methodology for developing a compound flooding model using long term data collection and basic stochastic hydrology

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Coastal regions across the globe have become increasingly susceptible to flooding impacts associated with urbanization, hydromodification, changing weather patterns, and tropical storm systems. However, when flooding occurs in coastal environments, it can rarely be attributed to one single hydrologic driver. In many cases, flooding in this environment can be considered as "Compound Flooding;" that is flooding that results from the combined effects of several different hydrologic behaviors, specifically rainfall-runoff processes and tidal forces. The complex flood behaviors of systems affected by both tidal forces and rainfall-runoff processes are often simulated using hydrology and hydraulic modeling software packages. The process of developing and operating computational models capable of accurately simulating these behaviors is resource intensive, and without proper calibration and verification, these models are capable of grossly misrepresenting system behaviors. As an alternative, this study presents a method for predicting general flood behaviors using simple mathematical models developed using field data collection, long-term monitoring, and basic statistical hydrology analyses.

For this study, water level and rainfall depth recording instrumentation were installed along a tidally influenced tributary of the Ashley River, called Church Creek, located in Charleston, SC. Using data collected from this gage station, along with publicly available data from a series of gages operated by federal science agencies, a series of mathematical analyses were used to isolate the effects of tide and rainfall-runoff on the peak water level of Church Creek. After isolating the separate effects of these two processes, a "Compound Flooding Function" was developed for predicting the peak water level in Church Creek based on the peak tide in the Ashley River and a multi-day rainfall total in the watershed. Using the function, joint-probability analyses were then used to investigate the recurrence of flooding based on a range of tide conditions and rainfall depths.

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Adaptive management for aquatic species recovery in the Apalachicola-Chattahoochee-Flint river basin

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The Apalachicola-Chattahoochee-Flint (ACF) river basin, from headwaters in north Georgia, to the Apalachicola Bay and estuary, is a focal geography in the Southeast with numerous listed and at-risk species; allocation of water for multiple uses in the ACF basin has been contentious and the subject of a legal battle among the States for decades. The Supreme Court ruling on the FL v. GA original action was issued in June 2018, and new hearings were initiated in November 2019; the legal process continues. However, working collaboratively among Department of Interior partners, US Army Corps of Engineers (USACE), and other stakeholders is critical to achieving desired Fish and Wildlife Service recovery and conservation outcomes in the basin. Consequent to a new USACE Water Control Manual, the Service prepared a Biological Opinion for six unionid mussels and Gulf Sturgeon and an adaptive management (AM) process for water management operations has been initiated to minimize take of the listed species. In this paper we describe the set-up phase for adaptive management that has proceeded with a steering team and a large expert stakeholder group. Subject matter experts developed Conceptual Ecological Models that link biotic responses to water management operations including levels of uncertainty in the management system. Through the AM process and monitoring, appropriate water management alternatives will be identified and incorporated into future conservation planning.

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Strengthening resiliency in coastal watersheds by protecting ecosystem services: A web-based GIS map viewer decision support system

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To promote and strengthen the resiliency of coastal watersheds in the face of increasing extreme weather events and development, ecological outcomes as well as socioeconomic issues need to be considered. A coastal watershed resiliency decision support system (DSS) is being developed to strengthen the resiliency and sustainability of coastal communities. The DSS integrates measures of ecosystem goods and services (EGS) and ecological integrity within a geospatial platform, allowing for spatially-explicit analysis of individual ecological units and their associated EGS at multiple scales, combined with socio-demographic data important to resilience and vulnerability assessment. The DSS and the metrics within it are intended to promote a more integrated and structured assessment of coupled ecosystem service and human wellbeing improvements that could result from different desired end states, resilience goals, or stages of restoration and resilience planning. The DSS provides web-based and mobile applications developed for a range of users from technical users to the general public. The framework integrates EGS or benefits and associated metrics (protection against extreme events/floods, water quantity/quality protection, habitat protection and open space conservation), considered important in informing decision-making to strengthen community resiliency and inform community restoration and revitalization goals. Using a Rapid Benefit Indicators (RBI) approach the DSS produces a set of indicators (scoring factors) and an evidence-based platform to help decision makers identify which community assets and vulnerabilities (contaminated sites within communities; vulnerable populations) are being protected or enhanced by existing EGSs in their watershed, and to assess the relative contribution of proposed EGS improvements or restoration options to improve social and ecological resilience. The easily understandable and comparable RBI metrics in the DSS allow users to compare and assess the impact of different restoration options and to (re)assess progress at different stages of restoration or improvement. Translating ecosystem services to resilience, and ecosystem service improvements to strengthen resiliency fills an important capability gap for resilience planning professionals in coastal states and communities.

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Longleaf pine forest restoration increases isolated wetland hydroperiod in the Gulf Coastal Plain of southeastern U.S.

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Jones Center at Ichauway

Geographically isolated wetlands (GIWs) are well known as "hotspots" for biodiversity and other ecosystem services, making their value on landscapes disproportionate to the area they occupy. GIWs are dependent on regular cycles of inundation and drying which makes hydrology a primary controlling variable for sustaining functions and associated ecosystem services. Although human activity has degraded GIWs in many regions, relatively little work has focused on upland management as a way of sustaining, or even improving, GIW structure and function. We present a case study of longleaf pine forest restoration, by hardwood removal, on the characteristics of wetland hydroperiod over a 10 year study. Our study wetland, W51, is 0.89 ha with a catchment area of 31.2 ha located on a ~11,400 ha private forest in Baker County Georgia (31.250 N, 84.495 W). Beginning in 2006, continuous water level and climate data were recorded in the wetland and adjacent well transects across the wetland catchment. In autumn 2009, hardwoods were removed or deadened in the catchment resulting in a 37% reduction in basal area. The effects on the hydrologic system were measured through 2016 by examining pre- and post-removal water levels, water yield-ecosystem (WYe), and standardized recession rates (RRstd). The study included periods of above and below normal rainfall. Generally, wetland hydroperiods began in December and ended in May, but varied with rainfall pattern and amount. Hardwood removal increased WYe and decreased RRstd resulting in greater catchment water availability as reflected in water levels. Hardwood removal affected both the ascending and recessing limbs of wetland hydroperiods, substantially increasing the availability of ponded water in the wetland. Our results provide direct measures of changes in wetland hydrologic characteristics associated with forest management and subsequent changes in forest water demand. Better understanding these relations has implications at both the local scale, i.e., managing critical aquatic habitat for wildlife populations, and at a regional scale, i.e., providing support for landscape scale connectivity and water yields.

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Section 10: Watershed Response to Intensifying Precipitation Extremes and Adaptation Strategies: Science and Management Challenges, Special Session

Watershed Management and Hazard Mitigation Planning: Collaborative Benefits in a Changing Climate

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With the increase in frequency and duration of severe weather events becoming the new normal, communities are facing growing pressure to develop plans that protect vulnerable populations and infrastructure. In Kentucky, and elsewhere around the nation, flooding and water quantity are issues of considerable concern. Within the goals of protecting water quality and controlling water quantity are solutions that are dual purpose, thereby providing a unique opportunity to strengthen mitigation and management efforts. Extreme rain events can exacerbate runoff of water quality-degrading pollutants, such as sediments and nutrients (e.g., Kaushal, et al. 2014). Green infrastructure that provides filtration of pollutants from stormwater runoff may also slow flows and improve infiltration reducing erosion and flooding. Authored every five years, federally-mandated Hazard Mitigation Plans (HMPs) aim to prevent, mitigate, and/or respond to high-risk climate events, like flooding. Successful HMPs build partnerships involving governmental agencies, non-governmental organizations, businesses, and the public; identify management strategies and implementation approaches; increase awareness of hazards through outreach and education programs; and synthesize all these efforts to effectively communicate priorities to leverage funding. These plans tend to involve water quantity-focused initiatives, and historically do not engage in watershed-based management approaches that would integrate water quality considerations. Like HMPs, Watershed Plan (WSP) development utilizes a phased approach: data collection, assessment and targeting, and strategy development and implementation establishes a plan that reflects the interdependency of natural resource uses, wide-ranging stakeholder interests, and ecosystem functions and services. Analogous to HMPs, they rely on committed stakeholder partnerships, geographic focus, scientifically sound management practices, and coordinated education and outreach strategies. However, water quantity is often not emphasized in WSPs, as their primary goals are to improve water quality metrics. Given the parallels between watershed and hazard mitigation planning, collaboration can provide a thorough and enhanced planning process that expands available funding sources, better informs selection and implementation strategies, and increases public awareness of the link between water quality and quantity issues. In this presentation, we describe how federal and state agencies partner with universities, regional planners, and municipalities in Kentucky to dovetail watershed and hazard mitigation plans.

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Spatial downscaling of precipitation data using advanced machine learning at the watershed scale

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***Lawrence Berkeley National Laboratory**
****Oak Ridge National Laboratory"**

Precipitation data serves as a critical forcing input for hydrology models. The highest available spatial resolution is 800 m (PRISM) for the continental United States, whereas higher resolution precipitation (< 100 m) inputs are needed for enhanced predictive capabilities. Here we present a machine learning framework to spatially downscale available coarse-resolution precipitation (~12.5 km) from NLDAS-2 models by utilizing point measurements of precipitation available from several NOAA and NRCS weather stations in the Upper Colorado Water Resource Region (UCWRR). First, we aggregate weather station data and subject them to quality control to identify missing records. We impute missing station data by learning co-variability with stations that have complete records. Next, we use weather station data to generate high-resolution (~100m) gridded precipitation estimates that serve as a ground-truth for downscaling. We consider weather station data both near to and far from an area of interest to investigate inherent multi-scale spatial patterns that influence precipitation. Finally, we train an algorithm that undertakes the actual spatial downscaling. At every step, we leverage (i) high-resolution spatial features such as elevation and vegetation, and (ii) seasonal variations, and use Random Forests to identify the relative importance of different features. Preliminary results indicate that the proposed approach enables us to generate and downscale to high-resolution precipitation with reasonable accuracy. We observe that precipitation patterns in UCWRR are influenced by elevation and seasons. However, additional features are needed (e.g., cloud cover, topographic slope) to accurately quantify the spatial and temporal factors affecting precipitation at fine scales. This work was supported by the ExaSheds project funded through the DOE Office of Science.

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Extreme Events Simulated by Dynamical Downscaling

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Extreme weather events—such as heat waves, drought, flooding, and tropical cyclones—can have catastrophic impacts on society. These extreme events can adversely affect the economy, infrastructure, ecosystems, agriculture, transportation, air quality, and human health. Governing organizations typically account for extreme events to some degree in their planning processes to minimize the impacts of extreme events.

There is a growing consensus in the literature that extreme events are likely to intensify through this century. Consequently, more emphasis has been placed on quantifying the changes to the frequency and intensity of these events. Several modeling techniques have been used to project potential changes to weather and climate across the next century, and there are several public data sets available that are currently used by federal, state, and local agencies to aid in the decision-making process. However, not all data sets can characterize the extremes associated with these events.

In this study, the Weather Research and Forecasting (WRF) model is configured as a regional climate model, and simulations are conducted on historical (verifiable) data sets to emulate the dynamical downscaling procedure that would be applied to refine global climate model projections. Here, we use 36-km and 12-km modeling domains, and we compare categories of extreme weather events that would influence governmental planning organizations. We evaluate these WRF simulations against observations to demonstrate the trade-offs between the computational expense of 12-km modeling domain versus developing a broader ensemble at 36-km on extreme event realization.

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Changes in the Future Extreme Precipitation Using Dynamically Downscaled Simulations From 2025 to 2100 for three forested and three urban stations in Southeastern U.S. Watersheds

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ORISE fellow at USEPA

The increasing trend in the frequency and intensity of extreme precipitation events and associated flooding has been well documented within the Southeastern U.S. using historical climate records. Studies have also described dramatic system changes associated with the observed extreme precipitation, such as ecosystem responses to extreme flood events with a plausible regime shifts in the intensity and quantity of runoff within some watersheds. Furthermore, climate models indicate that precipitation intensification will continue to increase throughout the twenty-first century. Precipitation Intensity-Duration-Frequency (PIDF) curves are a common tool used to account for extreme precipitation events in urban, forest and environmental planning. The PIDF curves estimate a frequency of occurrence (RP) of extreme rain events based on frequency analyses of the available data. Extreme precipitation events in recent years, proved that structures designed for the traditional (historic) PIDFs, fail because they cannot facilitate an excess rainfall. To address arising challenges related to changing precipitation characteristics, regulatory and managing bodies are seeking information to prepare for future weather patterns, which can be provided by the modelling community.

This study presents analyses of the trends in extreme precipitation probabilities for 76 years in the future (2025-2100) in three forested and three urban sites in the Southeastern U.S. The Weather Research and Forecasting (WRF) model was used to dynamically downscale two global climate models to 36-km for the moderate and highest greenhouse gas emission scenario (RCP4.5 and 8.5). The dynamically downscaled global climate models used in the study (the Community Earth System Model and the Geophysical Fluid Dynamics Laboratory coupled climate model) indicate up to a 30% increase in the annual maximum precipitation by 2100, and an increased variability in the intensity and frequency of the extreme precipitation. The one-hundred-year rain quantity increased up to 108% in the 1-h duration and up to 57% in 24-h duration. These results have implications in in design of storm-water management infrastructure, flood discharge estimates based on the future PIDF curves, and in transportation design and risk analysis. The study acknowledges that model uncertainties associated with model resolution or changes in spatial variability of extreme precipitation require further research.

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USA Continental Scale Intensification of Sub-daily Precipitation Intensities from ARS Experimental Watersheds

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Evidence is building that precipitation is intensifying more rapidly over short time scales (up to a few hours) that may result in increasing flood peaks and soil erosion. However, the paucity of sub-daily precipitation observations has limited the number of studies investigating temporal trends to analysis using a few isolated rain gauges or to global and regional climate models. The United States Department of Agriculture (USDA)-Agriculture Research Service (ARS) Long-Term Agroecosystem Research (LTAR) network has been systematically and professionally measuring and archiving sub-daily precipitation since the mid-twentieth century and its database represents a unique opportunity to evaluate temporal changes across different hydroclimatic environments. The goals of this study are: 1) to identify temporal trends in sub-daily precipitation intensities across different climatic regions for the period 1970-2013; 2) to evaluate if reported increases in rainfall intensities at the daily and hourly time scales observed at sub-hourly durations; and 3) to quantify the impacts of more intense precipitation on agricultural lands as measured by changes in soil erosivity and erosion. Our results show positive increases in precipitation intensities in the Northeast, Midwest, and Southwest regions at sub-daily scales ranging from 10 minutes to daily. Changes in precipitation intensities are more evident for the most intense events, events happening on average once a year, in the most recent years (1993-2013) compared to the earlier (1970-1992) period.

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A Comparison of Dynamical and Statistical Downscaled Climate Change Projections to Inform Future Precipitation Intensity-Duration-Frequency Curves

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Ryan Emanuel (NCSU), **Jaime Collazo** (USGS, NCSU)

A warmer climate creates an atmosphere that is more favorable for intense rainfall. Despite this simple thermodynamic relationship between atmospheric moisture capacity and temperature, a comprehensive understanding of precipitation extremes as the climate warms is a quickly evolving science as a result of recent historical rainfall events and improved computational resources. Simultaneously, many stakeholders (e.g., engineers, natural and cultural resource managers) are considering how they should adapt to climate change. This requires stakeholders and climate scientists to work together to use the best available science for the spatiotemporal scale of the application.

This study compares dynamically and statistically downscaled projections of global climate models to inform future IDF curves. Dynamically downscaled data, which are high-resolution model experiments of the future climate, have the ability to represent non-linear physical processes like hourly precipitation at spatiotemporal scales applicable to stormwater management and design. They are also useful tools in understanding the atmospheric conditions associated with extreme events. Unfortunately, these high-resolution climate model simulations are both costly and time consuming which limits our ability to diagnose uncertainty. There are additional constraints with using simulated data from many dynamical downscaling, such as inheriting biases from the global climate model. On the other hand, statistically downscaled projections are computationally efficient, can remove the global climate model bias, and available for many future realizations to investigate the issue of uncertainty. Statistically downscaled methods still have drawbacks. Climate stationarity is assumed, and data are limited to fewer parameters at daily temporal intervals which restricts the applicability for extreme sub-daily precipitation analysis.

Here we will compare two future downscaled realizations of the Community Earth System Model (CESM) using the dynamical and statistical downscaled methods for three forested watersheds from 2025-2100. The highest greenhouse gas emission scenario (RCP8.5) is examined to investigate a plausible, worst-case scenario. We will illustrate similarities and differences between these two methods for deriving future IDF curves and investigate the advantages of having sub-daily precipitation from dynamically downscaled simulations.

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Conversion of an Appalachian hardwood forest to a Norway spruce plantation: effects on hydrologic processes and function

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The U.S. Department of Agriculture Forest Service Fernow Experimental Forest (FEF) located in north-central West Virginia was established in 1934 on land purchased for the first tract of the Monongahela National Forest. Studies of forest management impacts on hydrology first began in the 1960s. In 1973, a 21.9-ha watershed at FEF was planted with 2-0 Norway spruce (*Picea abies*) seedlings, to evaluate the effects of conifer vegetation on streamflow and water quality. Considerable effort was needed to ensure survival of the Norway spruce "island" in the sea of hardwoods via herbicide applications in 1977 and 1980. After 47 years of tree growth and stand development, we report the effects of the forest type conversion on water yield relative to two control watersheds of native Appalachian hardwoods [WS4 (38.9 ha) and WS7 (23.7 ha), stand age approximately 100 and 51 years, respectively]. Dominant tree species include Northern red oak (*Quercus rubra*), black cherry (*Prunus serotina*), sugar maple (*Acer saccharum*), and yellow poplar (*Liriodendron tulipifera*). Current basal area is 43 m^2 ha^{-1} in WS6, and 114 m^2 ha^{-1} and 36 m^2 ha^{-1} in WS4 and WS7, respectively. Overall, annual precipitation has not significantly changed in any watershed since the 1950s and is approximately 145 cm yr^{-1}, though a weak trend of increasing dormant season precipitation was noted. No changes in intense precipitation events have occurred. Stream discharge from both WS6 and WS7 follow the discharge of WS4 closely in the pre-treatment period (1957–1964) (fig. 1). Discharge increased in WS6 and WS7 after harvesting and herbicide treatments relative to WS4 until the late 1980s. No change in annual discharge from WS4 has occurred. Beginning after 1994, WS6 exhibits significantly lower annual discharge than both WS4 and WS7 (fig. 1). Additionally, WS7 exhibits greater annual discharge than WS4 beginning after 2010, as well as a larger runoff ratio (discharge/precipitation). When stream discharge is analyzed seasonally, growing season discharge has declined faster in WS7 relative to WS6. Dormant season discharge in WS6 has decreased dramatically beginning in the late 1980s relative to both WS4 and WS7. Dormant season discharge in WS7 remains elevated compared to WS4 and has increased after 2010, a pattern which may be attributable to changes in dominant species or basal area. Overall, the spruce vegetation has dramatically decreased stream discharge relative to the hardwood reference watersheds, especially in the dormant season. These changes in stream discharge in WS6 relative to the hardwood watersheds are attributed to greater annual transpiration and less throughfall by the spruce vegetation.

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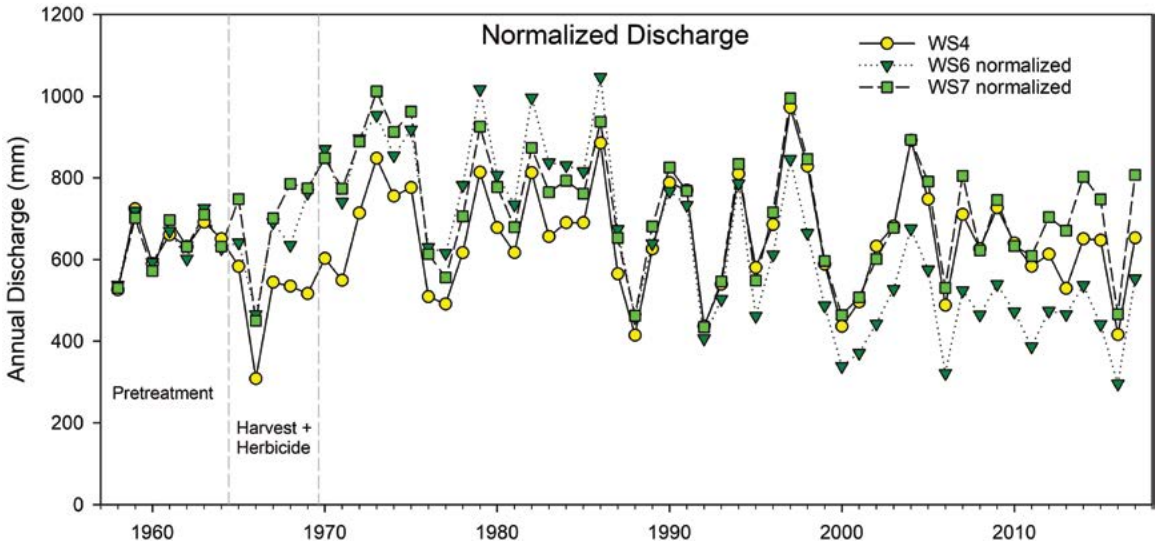

Figure 1—Annual discharge values (1954–2019) from streams draining the spruce-converted watershed (WS6) and two hardwood reference watersheds (WS4 and WS7) at the Fernow Experimental Forest, West Virginia. WS4 is the long-term hydrologic reference to which the watershed treatments are compared.

Additional ecosystem changes have been documented in WS6 relative to the hardwood control (WS7), including in water quality parameters, stand and biomass development, and nutrient cycling within the watershed. Current total above- and below-ground biomass estimates are slightly larger in hardwood WS7 at 294,500 kg ha^{-1} relative to spruce WS6 (259,000 kg ha^{-1}). Current estimates of total ecosystem carbon (C) and nitrogen (N) suggest that C pools are similar between watersheds, though total ecosystem N is still 13.4-percent lower in the spruce watershed, driven largely by lower mineral soil N content. The forest floor in WS6 also exhibits more than twice the mass and C and N storage relative to WS7, typical of a coniferous mor-type forest floor. Streamwater quality is also significantly altered, with very little nitrate being detected in the streamwater from WS6 since 1990, whereas nitrate export from WS7 exceeds the amount of atmospheric deposition (current nitrate export from WS7 is consistently over 10 kg N yr^{-1}). Differences in stream nitrate are reflected in N dynamics in the soil, and inorganic N content as extracted from field-fresh soil are 5.4 times larger in WS7 than WS6 (WS6 = 0.97; WS7 = 5.3 mg inorganic N kg^{-1} soil; $p < 0.001$). WS6 also exhibits significantly lower stream pH relative to WS7 (WS6 = 5.8; WS7 = 6.2) and soil pH (A-horizon soil pH_{CaCl} WS6 = 3.78; WS7 = 3.99), and relative to other FEF watersheds. The stream channel has also been altered because of changes in flow regime in WS6 and exhibits thick moss mats in the near-stream zone, which are not present in the stream in WS7. Conversion to spruce vegetation has fostered many ecosystem changes, particularly related to stream N export, an outcome which may be useful to watershed management efforts aimed towards mitigating N pollution to streams.

Section 11: Watershed Modeling (A)

Two-dimensional continuous simulation of watershed processes using a time-area hydrology model, HYSTAR

Young Gu Her, University of Florida

A time-area method was reformulated as a way to predict runoff hydrographs by explicitly describing spatiotemporally varied watershed processes. In a new hydrologic model, HYdrology Simulation using Time-ARea method (HYSTAR), the method was integrated with a simple routing scheme and modified curve number methods to simulate watershed dynamics. We evaluated the applicability of the time-area model in predicting the runoff processes of four study watersheds that have different landscapes, including a rolling upland (Virginia), a shallow forest wetland (Florida), and mountain forests (Brazil and South Korea). We also assessed the efficiency of parallelizing the time-area routing methods with multiple processors on a common personal computer. For demonstrating the utility of the model and further evaluating the soundness of the modeling strategy, hydrologically sensitive areas identified using model outputs were compared with the maps of topographic wetness indices. Results showed the potential of the method as a tool for watershed management planning. Finally, we discussed the limitations and future improvement directions of the model.

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Coupled terrestrial and aquatic carbon modeling towards improved watershed sustainability assessment

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The coupled carbon cycle across terrestrial and aquatic environments forms the basis of numerous lives on earth, holds the promise to explain gaps in the global carbon cycle, and provides essential services relevant to human and ecosystem health. The lack of watershed scale carbon models represents a critical impediment to understanding effects that human and natural factors have on our land and water resources. Here, we present an effort that puts together pieces of the terrestrial and aquatic carbon cycle at the watershed scale, by integrating multiple models, including SWAT, DayCENT, QUAL2K, and CE-QUAL-W2. We evaluate the model performance with respect to components of both terrestrial and aquatic carbon cycling processes and demonstrate its use to understand carbon budgets and ecosystem services at the watershed scale. In addition, we will discuss important parameters and processes regulating watershed carbon cycling and associated uncertainties.

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Effect of wetland and depression water storage on continental-scale hydrologic dynamics

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Process-based model simulations of droughts, floods, and water quality in response to watershed management typically focus on integrating large, managed water bodies (such as lakes and reservoirs) into the modeling efforts. Surface water storage in small yet abundant landscape depressions – including wetlands and other small waterbodies – is largely disregarded in conventional hydrologic modeling practices. No quantitative evidence exists of how their exclusion may lead to potentially inaccurate model projections and understanding of hydrologic dynamics in response to variations in climate and land cover changes across the world's major river basins. To fill this knowledge gap, we developed the first-ever surface depression-integrated continental-scale modeling approach, focusing on the ~450,000 km^2 Upper Mississippi River Basin (UMRB) in the United States. We applied a novel topography-based algorithm to estimate areas and volumes of ~455,000 surface depressions across the UMRB and then aggregated their effects per subbasin. Compared to a "no depression" conventional model, our depression-integrated model (i) improved streamflow simulation accuracy with increasing upstream abundance of depression storage, (ii) significantly altered the spatial patterns and magnitudes of water yields across 315,000 km^2 (70%) of the basin area, and (iii) provided realistic spatial distributions of rootzone wetness conditions corresponding to satellite-based data. These findings provide us with new insights on the effects of wetland and depression storage at large river basin scales and stimulates a reassessment of current conventional practices for continental-scale hydrologic modeling and management.

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Modeling Interactions of Riverine Flow and Riparian Vegetation for Quantifying Recruitment and Survival of Native Vegetation in California

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Life cycles of riparian vegetation are substantially impacted by river flow regime, groundwater and morphodynamics. A riparian vegetation simulation module was developed and integrated into HEC-RAS to predict seed germination, seedling establishment, plant growth and mortality in response to fluvial processes. The HEC-RAS vegetation model was applied to both Sacramento River and Santa Ana River reaches to predict temporal and spatial changes of riparian vegetation and the interactions between flow and riparian vegetation dynamics. River hydraulics, groundwater level and five vegetation types of the study reach were simulated. Model results demonstrate that the HEC-RAS vegetation model is capable of predicting the land coverage changes of cottonwood, mulefat. riparian shrub, mixed forest, and invasive species over a long period. The model was able to capture sites for cottonwood establishment observed on certain point bars. The modeled variations of cottonwood coverage in response to dynamic flow regime facilitated managing environmental flow for riparian vegetation restoration.

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Wetness Index based on Landscape position and Topography (WILT): Modifying the TWI to incorporate landscape position relative to water bodies

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USDA-ARS

Water and land resource management planning benefits greatly from accurate prediction and understanding of the spatial distribution of wetness. The topographic wetness index (TWI) was conceived to predict relative surface wetness, and thus hydrologic responsiveness, across a watershed based on the assumption that shallow slope-parallel flow is a major driver of the movement and distribution of soil water. The index has been extensively used in modeling of landscape characteristics responsive to wetness, and some studies have shown the TWI performs well in landscapes where interflow is a dominant process. However, groundwater flow dominates the hydrology of low-slope landscapes with high subsurface conductivities, and the TWI assumptions are not likely to perform well in such environments. For groundwater dominated systems, we propose a hybrid wetness index (Wetness Index based on Landscape position and Topography, WILT) that inversely weights the upslope contributing area by the distance to the nearest surface water feature and the depth to groundwater. When explicit depth to groundwater data are not available, height above and separation from surface water features can act as surrogates for proximity to groundwater. The resulting WILT map provides a more realistic spatial distribution of relative wetness across a low-slope Coastal Plain landscape as demonstrated by improved prediction of hydric soils, depth to groundwater, nitrogen and carbon concentrations in the A horizon of the soil profile, and sensitivity to DEM scale.

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Section 12: Advancing Watershed Science Using Machine Learning, Diverse Data, and Mechanistic Modeling, Special Session

AI to Advance Watershed Co-Design: Toward Seamless Interactions between Diverse, Multi-Scale Watershed Data, Models and Hardware

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While watersheds are recognized as the Earth's key functional unit for assessing and managing water resources, developing a predictive understanding of how watersheds respond to perturbations is challenging due to the complex nature of watersheds. This is particularly true in mountainous watersheds, where extreme lateral gradients in hydrogeology, biogeochemistry and vegetation often exist, and where perturbations (such as early snowmelt) can lead to changes in process interactions that potentially affect downgradient water, nutrient, carbon and contaminant exports. The Watershed Function Scientific Focus Area (SFA) project, which is being carried out in the mountainous East River, CO headwater catchment of the Upper Colorado River Basin, aims to develop a predictive understanding of watershed hydrobiogeochemical response to perturbations. The SFA is developing and testing several new constructs to accurately yet tractably quantify and predict multi-scale hydrobiogeochemical dynamics – from summit to receiving waters, across bedrock through canopy compartments and across terrestrial-aquatic interfaces.

One construct that the Watershed Function project is developing is the use of Artificial Intelligence (AI) to advance Watershed Co-Design, which focuses on advancing a deep and seamless marriage between diverse watershed data; mechanistic, multi-scale watershed models; and sensing networks. We illustrate recent advances in the use of AI for advancing aspects of the Co-Design vision, with examples largely associated with the East River testbed. One example includes the use of AI approaches to estimate the distribution of plant communities and microtopographic controls over plant ecosystem niches. The project is jointly assessing an unparalleled collection of vegetation and other 2D stacked watershed data layers - which together are providing 3D information about the spatial variability of bedrock porosity, soil thickness, digital elevation, vegetation characteristics, and snow thickness. For the first time, data-driven methods are being used to delineate watershed zones from these layers that have unique distributions of above-and-below ground properties relative to their neighbors. With the concept that these watershed functional zones will influence the quality and quantity of water exported from that particular parcel, intensive above-and-below ground monitoring systems have been set up in select zones to autonomously 'watch' fluids move between watershed compartments over the 4th dimension of time, revealing key spatial and temporal trends or transitions using AI. Reduced-order models are being used to accurately predict near term groundwater levels based on commonly available weather predictions. In practice, we believe that Co-Design enabled by AI, paired with data, models, and sensing networks, hold significant potential to accelerate real-time decisions and watershed management. More information about the SFA is provided at watershed.lbl.gov.

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Quantifying the Influence of Matrix Diffusion in Fractured Bedrock on Solute Retention and Transport at the Hillslope Scale

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Transit time distributions provide an integrated measure of the internal transport and retention processes that control the hydrologic and biogeochemical functioning of watersheds. There is a long history of research on watershed transit time distributions, evolving from lumped parameter models introduced in the early 1980s, to more recent works that emphasize time-variable transit time distributions and increasingly high-fidelity subsurface flow and transport simulations. In many low-order watersheds, significant flow occurs through fractured bedrock and transport and retention of solutes is influenced by matrix diffusion. Interestingly, although the importance of matrix diffusion was first recognized in attempts to reconcile anomalous water ages, the contribution of matrix diffusion to long-tailed transit time distributions in watersheds is seldom explicitly highlighted. There are significant computational challenges in incorporating matrix diffusion into watershed-scale flow and transport models. We present approaches to representing the influence of matrix diffusion within the framework of flowpaths generated by integrated watershed-scale hydrologic models. We illustrate the long-tailed transit time distributions resulting from matrix diffusion in models of hillslope groundwater flow. Matrix diffusion greatly extends the time horizon over which legacy nutrients and contaminants sequestered in the rock matrix elute into baseflow. In this context, we present approaches for quantifying the influence of matrix diffusion on lag times for recovery of receiving streams. Finally, we consider the influence of matrix diffusion in the frequency domain, and discuss its potential contributions to fractal stream chemistry, i.e. observations of fractal power spectra of the form 1/frequency^alpha (with alpha close to 1) in stream concentration fluctuations.

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Watersheds as natural spatial units for aggregating geospatial data for a global river bank erosion model

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As water, sediment, and nutrients move through watersheds, they accumulate towards outlets. Predicting these fluxes thus depends not only on local conditions, but also the upstream contributions of the basin. At a global scale, quantifying these contributions deterministically remains intractable, so empirical models relating upstream watershed characteristics to quantities measured at-a-point are often used. In order to quantify these upstream contributions at global scales, we developed the River and Basin Profiler (RaBPro), which leverages the HydroBasins global watershed delineations of basins of approximately 230 km^2. RaBPro rapidly delineates upstream areas for any given point globally. The resulting georeferenced basin polygons are then used for aggregating basin statistics for geospatial data, such as DEMs, climate outputs, vegetation indices, etc.

We will present an example of how this data-driven framework is coupled with statistical and machine learning techniques to identify drivers of riverbank erosion across the globe. The watershed-based drivers identified as important are used to develop a globally applicable model for riverbank erosion that can help estimate riverine carbon fluxes and provide clues toward which watershed characteristics and processes are most important across different regions.

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Simulating Hydrology's Role in Fire Behavior

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Half of the world's ecoregions are fire-dependent – meaning that fire disturbances will in some way affect ecosystem services including water resources and critical habitat for threatened and endangered species. The longleaf pine ecosystem of the Southeastern United States is one example of many fire-dependent ecosystems where successive prescribed fire is currently used to manage ecosystem structure and function. However, climate change will likely affect both fire behavior and ecosystem response to fire disturbances by for example, attributing to conditions where temperature drought reduces fuel moisture loading or limits ecosystem response following fire. These new conditions will therefore change fire behavior and result in new ecosystem responses. Moreover, empirical fire behavior modeling techniques that are rooted in observations of current system dynamics will be biased toward past conditions and may not capture system behavior in novel climate conditions. Here mechanistic modeling based on the underlying physics of fire behavior and ecohydrologic response offers a possible path to understand fire-dependent ecosystem response in a climate perturbed condition. We demonstrate a proof of concept disturbance and response model (DRM) that incorporates a physics-based approach to simulating fire behavior, hydrologic conditions, and ecosystem response. The DRM is built from a fully coupled surface and subsurface hydrologic model (ParFlow) with an additional fuel moisture - energy balance component in order to resolve fuel moisture loading in varied climate conditions. Together these components provide fuel moisture conditions to a fire behavior model (FIRETEC) that resolves fire-atmosphere interactions. The fire disturbance simulated by FIRETEC then produces a fire disturbance footprint onto a longleaf pine ecosystem growth model (LLM) that simulates the growth of fire-dependent species. In turn, the LLM is used to both evaluate habitat suitability of species of concern as well as establish fuel loads for the succeeding fire disturbances. This cycled fire disturbance and response model then provides a metric to assess ecosystem condition as it evolves from successive fire disturbance. We can further demonstrate how changing fire behavior in response to unique fuel moisture profiles create different disturbance regimes, and further how those differing disturbance regimes produce altered ecosystem structure.

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Wavelet and entropy approaches for improved characterization of geochemical hot moments

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Biogeochemical hot moments are known to account for a high percentage of nutrient cycling within terrestrial and aquatic ecosystems. Despite such importance, the ability to effectively identify hot moments and their associated controls remains a significant challenge. Using a combination of hydrological, solid and aqueous geochemical, geological, microbial and meteorological datasets, as well as statistical techniques, we seek to identify relevant hot moments and quantify which properties most explain the temporal variability in solute concentrations. We present two novel classification schemes – Shannon's entropy and wavelet-entropy to classify and systematically interrogate complex, multivariate datasets without making assumptions regarding the nature of temporal structure and dependencies implicit in these datasets. We develop and test these approaches at two sites: (1) a floodplain aquifer along the Colorado River, and (2) a high-latitude Arctic location near Barrow, Alaska. Wavelet analysis results demonstrate that seasonal perturbations (~4 months) constitute hot moments that drive biogeochemical cycling in the Rifle floodplain, with such activity confined to hot spots corresponding to the anthropogenically-contaminated zone. In contrast, a different dominant frequency (~3 months) dominates chemically-reduced zones associated with elevated concentrations of organic matter, chemolithoautotrophic activity and reduced mineral phases. These results combined with entropy statistics were used to isolate the governing transport and/or biogeochemical processes driving these hot moments. At Barrow, entropy analysis showed that soil moisture, soil temperature and growing season productivity most explained the variability in carbon fluxes over three successive years. The correspondence between biogeochemical zonation, seasonal variability, and other site-specific interactions from this study provide the key controls governing biogeochemical cycling at these sites. Importantly, these wavelet and entropy approaches are providing a simple yet tractable approach to identify temporal patterns and extract the key climatic, soil, vegetation and geomorphic features controlling carbon cycling that can then be readily incorporated into models.

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Multi-criteria, time-dependent sensitivity analysis considering hydrologic signatures, model performance metrics, and forcing uncertainty

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The dynamics of parameter importance in earth systems modeling framework has been the focus of research in recent years. To investigate the changing aspects of parameter importance, we implemented the variogram analysis of response surfaces to characterize predictive uncertainty of the KINEROS2 physically-based distributed hydrologic model in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) and Long-Term Agro-ecosystem Research (LTAR) site. Parameter importance was assessed using the absolute and relative sensitivity indices for several time-variant (throughout the simulation period) and time-aggregate (average of a simulation) model response surfaces. Parameter importance analysis of several model signature responses that represent different modeling needs and objectives such as runoff volume, sediment yield, peak runoff, runoff duration, time to peak, lag time, and recession duration. The results showed the importance of the parameters varied considerably depending on the type of the model responses of interest, size of watersheds, the depth and intensity of rainfall, the rainfall distribution, and the location of the storm from the watershed outlet. Identification of the most sensitive parameters and the factors that influence them was useful for a comprehensive understanding of process-based models, the uncertainties in model predictions, and to reduce the workload and time required during model parameterization and calibration.

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Machine learning tools for predicting freshwater fish populations

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To address the lack of publicly available fish community data for most of U.S. lotic freshwater habitats, we developed scientific software modules and databases for predicting fish populations by NHDPlus (National Hydrography Dataset) ComId (Common Identifier) segment. We create customized Scikit-learn (Pedregosa and others 2011) machine learning pipelines to develop diverse predictive models. The dataset derives from U.S. Environmental Protection Agency, U.S. Geological Survey, and State agency records and contains 565 fish species observed through electrofishing in 28,519 stream segments identified by their ComId sampling locations. We use the observations of fish to develop a binary dataset for each species, labeling each observation as *present*(1) for each species found at least once by electrofishing in sampled ComIds. Then for each species, we use the collection of HUC8s (8 digit Hydrologic Unit Code) where that species may be found, and we label the unlabeled sampled ComIds as *absent*(0). To describe the catchment where each sampled ComId is located, we develop a set of 270 predictor variables for each sampled catchment by condensing the full collection of StreamCat metrics (Hill and others 2016) with operations such as retaining only an average of each landcover time series, dropping older iterations of multi-version metrics, and dropping meta-data variables.

Each machine learning pipeline starts with 10 nearest neighbors imputation for missing values in StreamCat and ends with a predictive statistical estimator that the pipeline is named after. For linear regression and support vector machine classifiers, regularization hyper-parameters are selected by including within those pipelines a nested, grid-search 5-fold cross-validation where parameters are chosen based on best average weighted F1-score, with weights used to balance the sample size for each label. The pipelines are as follows: lasso logistic regression, two support vector machines variations (with linear and radial-basis-function kernels), and two

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implementations of regression tree boosted ensemble classifiers. To quantify model accuracy, we use 20 repeats of stratified 5-fold cross-validation for most species; for several species with few observations, fewer folds are used to ensure that both labels appear in all test and training datasets. Species with too few observations (fewer than 32) or too few presence labels (fewer than 8) are dropped, leaving 524 species for modeling. Table 1 shows the relative cross-validation performance of each pipeline averaged across species.

Because each sampled ComId is included in the models for numerous species, we were able to aggregate information across species into a single map of the conterminous United States (CONUS) to develop spatially variable characterizations of the fish and model performance. Figure 1A shows the summed value of the dependent variable across species by ComId averaged up to the HUC6 level. Figure 1B shows the ComID True Positive rate averaged by HUC6, averaged over the five pipelines/classifiers and across species.

Results apply to lower (Strahler) order, wadeable streams. Results may be affected by sampling density, which is the greatest in the Appalachian States and in Minnesota. Electrofishing technique as well as effort may vary across the dataset as well. Due to the diverse and broad nature of the predictive measures afforded by the StreamCat dataset, these models are useful for prediction and ill-suited for causal inference due to high multi-collinearity and endogeneity.

Ongoing research includes the development of predictive species distribution maps for non-sampled ComIds of comparable stream order across CONUS. Other efforts are focusing on identifying species clusters, spatial outliers, and interpretation of model results. Measures of variable importance such as regression parameters can help researchers understand population dynamics, but our efforts to identify and visualize patterns in regression and linear support vector machine parameters across all species and in clusters of species are in progress. Future efforts may focus on identifying causal measures with quasi-experimental econometric approaches (e.g., differences in differences estimators) or on adapting occupation models to this large dataset with relatively few repeat visits. Expansion of the dataset is also a continuous effort. The code and data necessary to reproduce these results are available at https://github.com/DouglasPatton/fishmachine/tree/kernel270. Future work may also include integration of these tools into the existing browser-based software platform named PiSCES (Cyterski and others 2020).

Table 1—Classification Pipeline Cross Validation Accuracy Averaged Across 524 Species

	Balanced F1-Score	
Machine learning pipeline	**Mean**	**Standard deviation**
Gradient Boosting Ensemble	0.890021	0.074962
Histogram Gradient Boosting Ensemble	0.884668	0.085438
Support Vector Machine - RBF Kernel	0.873387	0.107455
Support Vector Machine - Linear Kernel	0.840138	0.085275
Regularized Logistic Regression	0.818346	0.077273

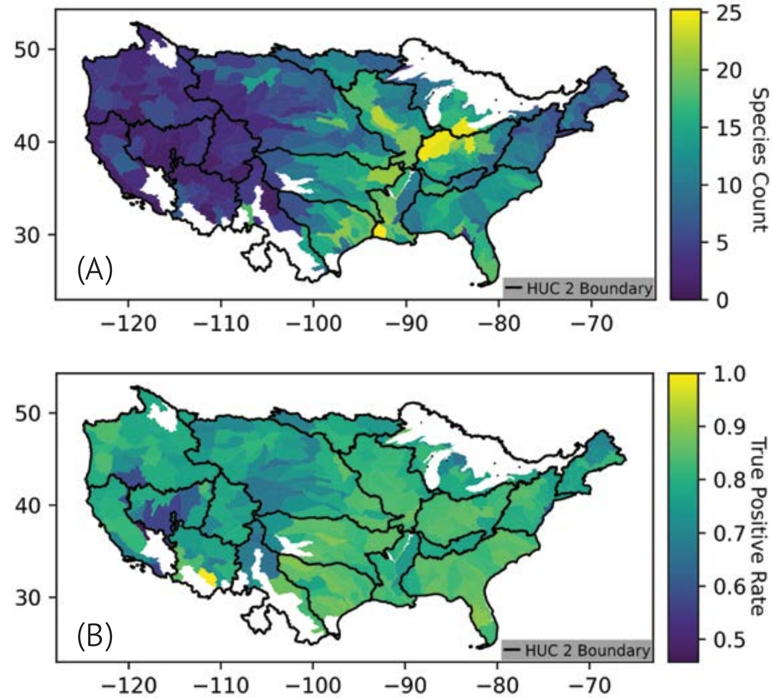

Figure 1—All species spatially stacked results, (A) HUC6 average ComId species count; (B) HUC6 average ComId true positive rate.

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What Role Does Hydrological Science Play in the Age of Machine Learning?

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Recent experiments applying deep learning to rainfall-runoff simulation indicate that there is significantly more information in large-scale hydrological data sets than hydrologists have been able to translate into theory or models. We argue that these results challenge certain `sacred cows' in the surface hydrology community, and may be a bellwether for the discipline as a whole. While there is growing interest in machine learning in the hydrological sciences community, in many ways our community still holds deeply subjective and non-evidence-based preferences for process understanding that has historically not translated into accurate theory, models, or predictions. The objective of this opinion piece is to suggest that, due to this failure in the surface hydrology community to develop scale-relevant theories, one possible future is a discipline based primarily in machine learning and other AI methods, with a more limited role for what we currently recognize as hydrological science. We do not want this to happen and suggest a `grand challenge' for the community to work toward demonstrating where and when hydrological theory provides information in a world dominated by big data.

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Section 13: Water Quality and Quantity (B)

An Investigation of Phosphorus Concentration Trends in Waters of the U.S.

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Conflicting evidence has emerged concerning the direction and magnitude of phosphorus changes in freshwaters of the northern hemisphere. While some studies have found consistent, unexplained phosphorus increases especially in low-nutrient systems, other studies have found no such widespread phosphorus changes. By contrast, several studies have documented widespread phosphorus declines in already-oligotrophic lakes of northern countries. To further investigate temporal trends in total phosphorus concentrations in U.S. waters, we employed large-scale compilations of available monitoring data

(LAGOS_NE and the Water Quality Portal). We evaluated total phosphorus data using linear and non-parametric regressions based on both individual samples and summer-mean concentrations, over various time spans (e.g., 1990-2013, 2000-2013). Distributions of slopes of TP vs. time were in general symmetrical around median values near zero, indicating a lack of predominant change in either direction (i.e., either increasing or decreasing). Investigations of time series in some individual systems suggest that apparent temporal trends derived from limited sampling are not supported by longer sequences of available data.

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Sub-Watershed Trace Element Regimes in Surface Waters of an Appalachian Mixed-Land-Use Watershed

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Geochemical impacts of land-use practices remain an area of greatly needed investigation. A nested-scale experimental watershed study was conducted in an urbanizing, mixed-land-use, Appalachian watershed to advance understanding. Twenty-two study sites, characterized by contrasting land use/land cover and drainage area, were instrumented to continuously monitor stream stage. Weekly grab samples were collected from each site during the 2018 annual year, and analyzed for trace element composition (Al, Cd, Co, Cu, Fe, Mn, Ni, Pb, Zn, and As) via spectrometric methods. Additional physico-chemical parameters, including pH, were measured at the time of sampling. Data were analyzed using a suite of statistical methods, including correlation analysis and Principle Component Analysis (PCA). Results showed a trend of increasing trace element concentrations associated with legacy industrial land use practices (i.e. mining) in the mid watershed, and subsequently decreasing concentrations in the downstream direction. PCA results highlight spatial differences between elemental composition and physico-chemical characteristics of streamwater samples. Results from correlation analyses indicated varying significant ($p < 0.05$) relationships between chemical parameters and hydroclimate metrics, suggesting the influence of contrasting flow paths and constituent sources. Given the geological, topographical, and climatological similarities between the sites, and their proximity to each other, it is concluded that land use characteristics and associated hydrologic regime contrasts were the primary factors contributing to the observed results. The applied methodology can be used to advance understanding of trace element regimes in mixed-use watersheds, and to more effectively target sub-watershed-scale remediation/restoration efforts, thereby improving the ultimate efficacy of management practices.

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A freshwater tidal wetland gradient for carbon cycling and hydrological investigations

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Tidal freshwater wetlands (TFW) occur between the tidal saltwater zones within estuaries and the non-tidal terrestrial waterways. Accordingly, ecosystem dynamics and biogeochemical processes in TFW are regulated by the additional hydrologic influence without the interaction with brackish waters. As a result of the tidal influences, TFW do not have the water regime that follows a seasonal cycle of wetting and drying and that are regulated by precipitation, groundwater, and evapotranspiration. Instead, it is mediated by tidal forcing that causes a vastly different soil water regime, with corresponding effects on soil redox conditions and associated biogeochemical processes. TFW occur as both marsh and forest vegetation, with marshes tending to occur downstream of the forested riparian zones due to differences in inundation depth and duration of the high-water table.

Freshwater tidal streams and wetlands function as a reservoir, sustaining elevated floodplain water tables irrespective of fluctuations in precipitation and evapotranspiration (Czwartacki 2013). Varying degrees of overbank flooding and floodplain drainage occurs on a daily basis, significantly increasing lateral exchanges between the stream and its floodplain in comparison to non-tidal wetlands. Biogeochemical processes including carbon sequestration, greenhouse gas emissions, and dissolved carbon fluxes are expected to be altered as well. Krauss and others (2018) recently reported the sensitivity of carbon stocks and fluxes within a tidal freshwater gradient, importantly documenting the relevance of these wetlands as part of Blue Carbon.

Since TFW occur at the upper reaches of estuaries, they are the interface between the terrestrial and marine environments. This interface between land and water systems is recognized as a critical zone that is fundamental to understanding carbon and nutrient dynamics at multiple scales (U.S. DOE 2017). Measurements of carbon stocks and fluxes from TFW are very few; hence additional information is needed to better constrain stock and flux estimates and provide a basis for model validation (Kolka and others 2018).

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We have established and instrumented a TFW gradient on the Santee Experimental Forest and South Carolina Department of Natural Resources land to provide the basis for studies to assess the tidal controls on wetland biogeochemical processes and ecosystem services. The catena includes: (a) freshwater tidal marsh, (b) two tidal bottomland hardwood forested wetland reaches, and (c) a non-tidal bottomland hardwood forest wetland (table 1). The two tidal forested wetlands sites are down stream of the transition from tidal to non-tidal riparian zone. The catena is located along the East Branch of the Cooper River and its tributaries, which is one of the major inputs to the Charleston estuary (fig. 1).

Monitoring on each of the four sites includes: (a) water table depth within the riparian zone, and (b) surface elevation tables, installed in 2020 enabling quantification of changes in the land surface over time. Attributes that will be incorporated include: stream conductivity and plots for vegetation assessments. A gauging station, instrumented with an acoustic doppler flowmeter, was established in April 2020, enabling quantification of stage and the bi-directional hydrologic fluxes approximately 500 m downstream of the tidal–non-tidal interface.

Work by Czwartacki (2013) studying the hydrology of the non-tidal to tidal transition zone and Farley (2017) who documented the importance of microtopography in greenhouse gas fluxes in TFW provided the foundation for this catena. Ongoing research is focused on greenhouse gas fluxes and the groundwater dynamics in terrestrial and tidally influenced forested wetlands along the gradient, and plans are to expand that to include the tidal marsh site. This catena is intended to provide a facility for research to address this important part of the coastal zone that is critical to addressing issues associated with climate change, sea level rise, and development, and their impacts on downstream estuaries.

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Access to the tidal marsh (Mayrant Lead) site is provided by the South Carolina Department of Natural Resources. We thank Julie Arnold, USDA Forest Service, for maintaining measurements and monitoring of this study facility. The surface elevation tables were installed by the U.S. Geological Survey, Wetland and Aquatic Research Center. The College of Charleston installed the Huger Creek gauging station and developed the rating curve in collaboration with Xylem Corp.

Table 1—Location, soil, and land cover information for the four study reaches within the tidal freshwater wetlands catena within the East Branch of the Cooper River, SC

Site	Latitude	Longitude	Soil Type[a]	Land Cover[b]
Tidal Marsh: Mayrant Lead	33.075043	-79.882628	Capers association (CP)	Emergent Herbaceous Wetlands (95)
Tidal BLH: Huger Ck 1 (Gauge)	33.131134	-79.809693	Meggett clay loam (Mp)	Woody Wetlands (90)
Tidal BLH Huger Ck 2	33.131436	-79.806591	Meggett loam (Mg)	Woody Wetlands (90)
Non-tidal BLH: Turkey Ck	33.126819	-79.777369	Duplin fine sandy loam, 2–6% slopes (DuB)	Woody Wetlands (90)

[a] Soil information: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx [Date accessed: Jan. 4, 2021].

[b] Vegetation information: https://www.mrlc.gov/data/references/national-land-cover-database-2016-landcover-imperviousness-nlcd2016 [Date accessed: Jan. 4, 2021].

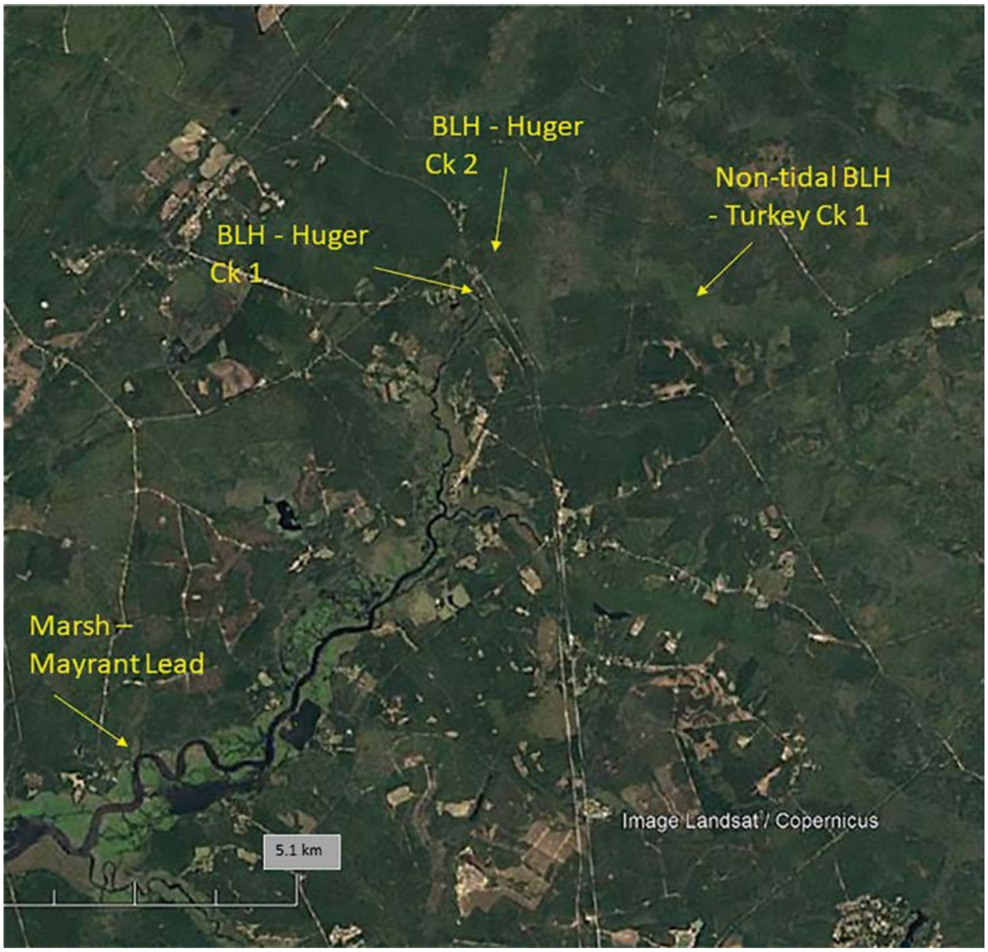

Figure 1—Location of the tidal freshwater wetland catena within the East Branch Cooper River watershed, South Carolina. Satellite image from Google Earth [Date accessed: June 16, 2020].

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Economic Analysis of Modern Irrigation Scheduling Strategies on Cotton Production under Different Tillage Systems in South Georgia

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Row crop producers use irrigation as a vital risk managing tool to achieve higher and more consistent yield. Even though cotton is a drought-tolerant crop, producers still use irrigation to increase yield and manage production risks. The depletion of the ground water has escalated at an alarming rate due to the heavy usage of irrigation for meeting the present demand in crop production in South Georgia. Therefore, to ensure water quality and avoiding water scarcity in the near future, several modern irrigation scheduling methods are being developed and practiced. The goal of this research is to compare economic efficiency of five different irrigation scheduling methods under conservation and conventional tillage systems to identify the most profitable method.

From 2013 to 2017, a cotton field experiment was conducted in Camilla, Georgia, to compare five modern irrigation scheduling methods with dryland production (control). University of Georgia (UGA) Checkbook Method, the Smart Irrigation Cotton App, the University of Georgia Smart Sensor Array (UGA SSA), the Irrigator Pro for cotton, and the Cotton Water Stress Index (CWSI) are the five modern irrigation scheduling methods investigated under conservation and conventional tillage practices. As for the dryland control, they were only used in the conservation tillage. Four cotton varieties were used each year to assess their performance in different irrigation scheduling methods. Cotton lint yield and lint quality was measured. The market price and loan price for cotton was calculated based on fiber quality for each year. Irrigation cost will be calculated using the irrigation budgets developed by UGA Extension. Net return will be calculated by subtracting irrigation cost, harvesting, and ginning costs from the gross revenue of cotton production.

Preliminary results show that water use efficiencies were negative during wet years in 2013, and 2015–2017. The lint yields, seed yields and gross revenue were higher for dryland production in those wet years. Cotton App had the highest average value for gross revenue among all the irrigation scheduling methods, especially in dry years like 2014.

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How does high input maize production affect water quality?

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There is a great concern about the impact of agriculture on the environment. Most farmers' goal is to achieve the highest possible yield. In Georgia, a relatively small group of farmers have been able to achieve maize yields of around 31000 kg/ha (500 bu/ac). In addition to better varieties and the use of irrigation, higher yields are often pursued by adding more agrochemicals and more specifically, higher rates of fertilizers. The use of high rates of fertilizers can result in unintended environmental consequences as unused fertilizers can move from the soil to groundwater with leaching and to streams and rivers with surface runoff. The impact on the environment has been documented by researchers for at least the past 50 years. As farmers pursue higher yields, the threat to the environment may increase. Previous studies have tried to find ways for better management practices which could possibly minimize the environmental problems. This three-year study focused on identifying the environmental effects, regarding water quality, of pursuing high maize yields in Georgia, USA. Groundwater and surface runoff samples were being collected throughout the years and analyzed in the lab for nitrogen, phosphorus, and other parameters. The data will be used to calibrate and validate Hydrus – 1D in order to understand how the system responds to different management practices used to achieve high maize yields. Moreover, the model will be used for simulating a wide range of management scenarios in order to identify the practices which result in the highest yields with the lowest adverse environmental effects.

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In-field hydrologic properties affected by sugarcane row spacing in south Louisiana

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Sugarcane (*Saccharum* spp.), is a perennial crop cultivated on over 180,000 ha in southern Louisiana. This humid, subtropical region is characterized by high annual rainfall (1650 mm), a shallow water table (< 1.5 m), and poor drainage. Sugarcane is widely cultivated in this region due to its adaptability to these challenging conditions. While most growers utilize the traditional 1.83-m row spacing, some growers have recently adopted a wider, 2.43-m row spacing. The wide row spacing increases planted area by 6% at the expense of furrow drains. However, we currently do not know how the practice affects the hydrology of the wide row system, and the potential effect on crop growth. Therefore, the objective of the research was to use meteorological and eddy flux data to compare hydrologic properties of each system between April and September, the most active growth period for sugarcane in Louisiana. Bi-phasic cane growth was linear from April thru May (0.50 cm d^{-1}) and June thru August (1.94 cm d^{-1}). Stalk counts were lower in the narrow rows (108,000 ha^{-1}), when compared to the wide rows (128,000 ha^{-1}). Rainfall totals for the same period were 885 and 977 mm, respectively. The mean volumetric soil moisture to 15 cm was lower for narrow rows (61.5 mm ha^{-1}), when compared to wide rows (72.7 mm ha^{-1}), but never dropped below 44.7 and 47.6 mm ha^{-1}, respectively. Evapotranspiration (ET), estimated using the FAO Penman-Monteith equation and Kc (0.4, 60 d; 1.25, 92 d), was 7% lower for narrow rows (737 mm, 4.9 mm d^{-1}), when compared to wide rows (788 mm, 5.2 mm d^{-1}). Measured ET using latent heat was 13% lower for narrow rows (436 mm, 2.87 mm d^{-1}), compared to the wide row configuration (500 mm, 3.33 mm d^{-1}), but flux-based ET was 40% (narrow row) and 37% lower (wide row), respectively, than ET estimated using the Penman-Monteith equation. These preliminary data indicate neither narrow nor wide row sugarcane appeared to be water stressed due to the relatively high amounts of rainfall observed and the reduced number of drains, as both production systems retained adequate soil moisture levels.

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Feasibility and implications of two approaches for estimating recharge from hydrologic events at the Panola Mountain Research Watershed, Georgia

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Recharge is an important process that sustains stream baseflow and impacts the availability of water resources. Recharge is often quantified by modeling or estimation from water budget analyses due to the lack of direct measurements. Hydrometric measurements from the Panola Mountain Research Watershed, a 41-hectare forested, seasonally water-limited catchment within the Piedmont Province of Southeastern United States, were used to quantify recharge during 469 storm events over a 12-year period using two approaches.

In the first approach, recharge was quantified from event water balances that included precipitation, change in shallow storage, potential evapotranspiration, and storm runoff. Approximately 23% of the events had recharge >1 cm, which was dependent upon pre-event soil moisture conditions and event precipitation. About 33% of annual recharge occurred in winter (January – March) when the watershed was wet and 33% occurred in summer (July – September) when precipitation was highest. Overall, recharge represented about 16% of precipitation. This approach appears to underestimate recharge because baseflow (as determined from a hydrograph separation) represented 21% of precipitation over the same period. Underestimates could be due to the lack of representation of the soil moisture profile variability across the watershed, the estimated soil storage depth, and the vertical resolution of the probes.

In the second approach, recharge was estimated as the change in deep storage during events as determined from a baseflow-watershed storage relationship and the change in shallow storage. The baseflow relationship was developed using a water balance approach combined with a recession analysis. This approach gave contradictory results to the water balance approach, indicating that recharge occurred predominantly during the fall (October – December; 27%) and winter (48%). This approach substantially overestimated recharge, because recharge represented about 51% of precipitation. In the winter, changes in deep storage frequently exceeded event precipitation, particularly when soil moisture conditions were near their maximums. Overestimates likely reflect expansion of variable source areas contributing to baseflow. This disconnect indicates that summer recharge does not contribute to baseflow until connectivity occurs. Improved understanding of recharge processes can provide insights for determining the sensitivity and resiliency of baseflow to droughts and potential climate change.

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Forty years of data: challenges and opportunities afforded by long-term data sets

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Abstract—The University of Kentucky (UK) Department of Forestry and Natural Resources has managed UK's Robinson Forest for over 40 years, conducting experiments crucial to understanding the environmental impacts of land management in the region. Part of the management of Robinson Forest has been collection of precipitation and streamwater data, including precipitation quantity, precipitation chemistry, streamflow, streamwater chemistry and temperature, and air temperature. Over the years, these data have been collected and archived using various technologies, and they have been mostly inaccessible for research use—unedited and uncompiled, scattered across a number of spreadsheets and paper records. Through a partnership between the U.S. Geological Survey (USGS) and UK, precipitation data for six stations and stream data from four watersheds in Robinson Forest have been compiled, checked for transcription errors, and annotated for changes in methodologies. These data are now available on ScienceBase (https://doi.org/10.5066/P9FPLG1O), an online data-access platform. Improved accessibility of this valuable data set provides an important research resource for understanding water quality in reference-quality forests in the region. Analysis is ongoing; however, preliminary results suggest that these data present a valuable opportunity to evaluate linkages among atmospheric deposition of nitrates and sulfates and stream chemistry, as well as the impacts of policy, such as the Clean Air Act. Furthermore, these data will allow for analysis of long- and short-term changes in air temperature and precipitation patterns over the last 45 years.

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Section 14: Watershed Modeling (B)

Groundwater and surface-water contamination susceptibility determination through automated geospatial models using combined modeling approach of DRASTIC and RUSLE

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In the 1970s, coal mining in Appalachians changed dramatically with the advent of mountaintop removal strip-mining. The result is catastrophic for both the environment and the people of this region due to the toxic byproducts the strip-mining generates. Dams constructed for the slurry impoundments can and do fail to pollute the streams downstream. The most tragic example was in 1972 when a dam failed, resulting in the deaths of 125 people along the Buffalo Creek Hollow. Reclamation, a major aspect pf mining, is the process of attempting to convert the mined area back to its previous state, by filling in the open mines and planting grass and shrubs. Mines are required by law to be reclaimed after the mining process has been completed. However, this process is flawed due to the use of compromised soil that was mined. As a result, the reclamation areas can barely support grasses and many areas remain bare, prone to soil erosion, which pollutes the rivers or wells of the region due to soil's toxicity. The goal of this study was to show the land-use change in the surface coal-mining in southern West Virginia and analyze its impact on ground- and surface-water quality in the region.

The area of interest (AOI) is the southern portion of the State of West Virginia. The study was completed by performing an object-based supervised classification of two multi-temporal (2008 and 2018) Landsat images and carrying out land-use change analysis. A groundwater contamination vulnerability DRASTIC model was developed to show the spatial vulnerability of groundwater pollution. Finally, a comprehensive soil erosion model, modified RUSLE model, was developed to show the erosion potential in active and post mined areas. A thorough literature review was conducted to find the possible bioenergy crop that can be grown in the ill-managed area with low maintenance for efficient reclamation. A Soil and Water Assessment Tool (SWAT) hydrologic model was completed to observe the reduction in soil erosion and water contamination.

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Land-use change analysis completed with NDVI developed for 2008 and 2018 showed the spatial extent within the AOI that have experienced regreening. Regreening areas were earlier mined while many reclaimed mining areas are still in barren state, thus explaining the reclamation process either working or failing.

A DRASTIC model looks at seven environmental conditions that can determine aquifer vulnerability due to surface pollutants (Babiker and others 2005). The factors associated with the DRASTIC models are the **D**epth of the water, net **R**echarge, **A**quifer Media, **S**oil Media, **T**opography, **I**mpact of the vadose zone, and Hydraulic **C**onductivity. A consensual model DRASTIC vulnerability rating equation used for determining groundwater contamination vulnerability is shown in Equation 1:

$$\text{DRASTIC index} = 5Dr + 4Rr + 3Ar + 2Sr + Tr + 5Ir + 3Cr \qquad [1]$$

where r represents the rating of individual factors of D, R, A, S, T, I, and C as explained above.

Data needed for this study were acquired from the University of West Virginia Geospatial Server, the USGS' Groundwater and evapotranspiration database, NOAA's PRISM meteorology database, and Web Soil Survey of the U.S. Department of Agriculture. The Delphi method-based weighted scale was compiled and used to develop the DRASTIC model to provide groundwater/aquifer contamination spatial vulnerability (fig. 1A). Major coal mining locations in the study area are very vulnerable to groundwater contamination as analyzed by correlating the location of surface mine refuse ponds and the vulnerability of groundwater pollution produced by this

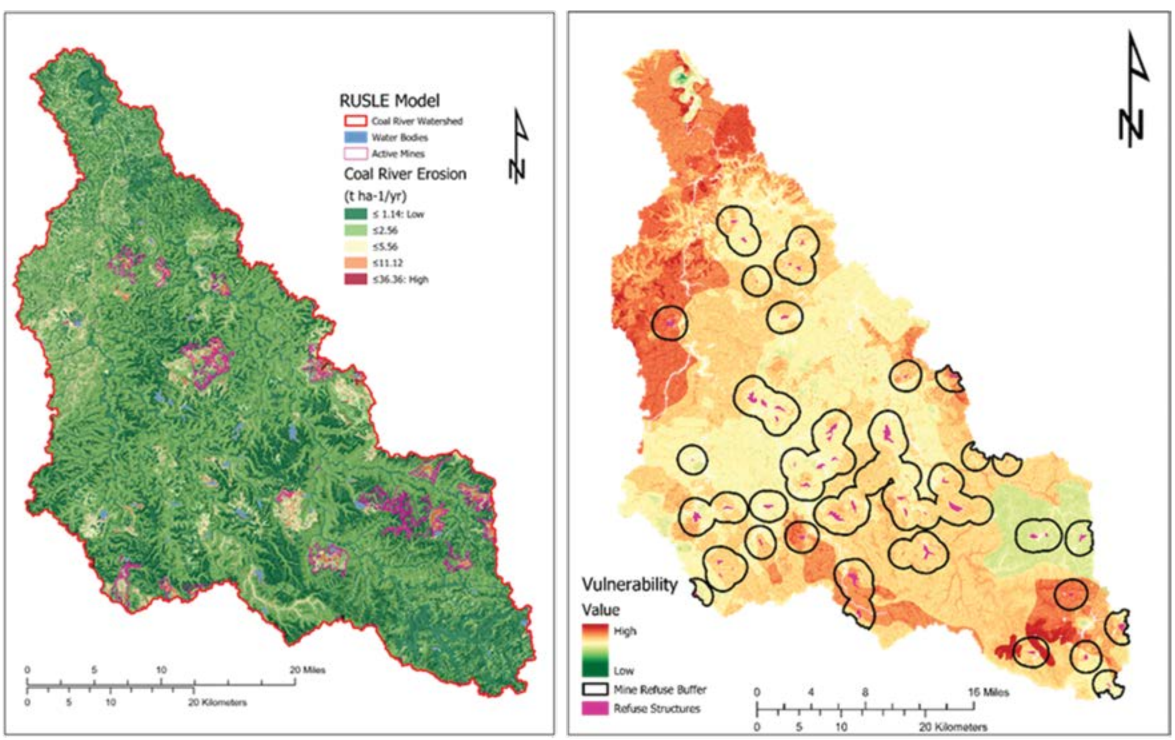

Figure 1—(A) Groundwater contamination spatial distribution map of the area of interest (AOI); (B) final soil erosion spatial distribution map of the AOI.

DRASTIC Index (fig. 1A). From our results, we observed that many slurry ponds are situated in the highly vulnerable groundwater contamination spatial zones and need to be constantly monitored.

A modified RUSLE soil erosion model was developed for the AOI with the unique development of the R-factor using NOAA PFDS 100-year 30 min. rainfall intensity raster of the study area, C-factor using an NDVI based formula ($C = 0.1(\frac{NDVI+1}{2})$), and P-factor using the classified land-use map of the study area. The K, L, and S factor rasters were developed from the STASGO2 data downloaded. Figure 1B is the output soil erosion distribution map of the AOI showing vulnerable spatial locations of severe soil erosion potential. We observed that major high soil erosion potential areas coincide with coalmines or slurry ponds. Therefore, environmental managers of the study area should be cautious in managing the watershed concerning soil and land-use reclamation. Interestingly, there are high rates of erosion around the refuse ponds created during the mining process. Areas of reclamation show up as moderate levels of erosion. Valley floors and ridgelines had, on average, the lowest erosion rates. Areas that maintain their dense forest cover saw comparatively little soil loss.

Sahoo and others (2019) used miscanthus (bioenergy crop) at reclaimed mines and found it advantageous in improving environmental quality. Our SWAT model of AOI with miscanthus as a cover crop (instead of the natural grass or shrub) obtained sediment and nitrate load reduction by ~1 percent and 7.7–22.5 percent, respectively. Thus, to reclaim we propose using bioenergy crops like miscanthus, switchgrass, and tannin-rich forage (e.g., lespedeza sericea, which can grow well in arid and semi-arid conditions and is best for rearing small ruminants) should be grown in the reclaimed areas.

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Trends in Deuterium Excess Coupled with Trends in Groundwater Levels Observed at Shingobee and Williams Lake, Minnesota Reveal Local Evaporative Processes

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Global Circulation Models have three main domains simulating atmosphere, oceans, and land surfaces with horizontal resolutions of 200 to 600 kilometers. Recent efforts to downscale atmospheric resolution to permit simulation of significant updrafts and downdrafts at mesoscale resolution (4 km) have shown that model predict warmer temperatures than observed, particularly around rivers and streams. The source of this bias has been attributed to lateral flow of groundwater providing moisture to otherwise parched soils, providing water for increased evaporation and, thus, lower air temperature. We test this hypothesis by looking at deuterium excess in precipitation, which is inversely related to evapotranspiration rates, measured in precipitation collected from 2005 through 2015. The deuterium excess was measured at two weather stations near lakes just east of Akeley, Minnesota: Shingobee Lake, where large groundwater inflows occur, and the nearby Williams Lake, a closed lake with no surface water inflow or outflows and drier shoreline margins. The trends in deuterium excess for the two lakes are inversely related, with Shingobee trending downward, and Williams Lake trending upward until an inflection in 2011. That year was coincident with the end of a 2000-2011 trend of decreasing water tables in the area. After 2011, seasonal precipitation maxima in the spring and summer shifted to the fall when ET is substantially smaller, thereby increasing groundwater recharge even though the total annual precipitation did not substantially change. If this paradigm is true, grids of observed deuterium-excess could provide critical new calibration targets for a new generation of high resolution land-atmosphere models.

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Non-Point Source Pollution Modelling under conservation practices in The Upper Choctawhatchee Watershed Using Soil and Water Assessment Tool (SWAT)

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Water quantity and quality modeling of the Choctawhatchee River Watershed was carried out using Soil and Water Assessment Tool (SWAT). Historical simulation spans over last three decades from 1990 to 2018. Several management practices were utilized to assess response of the hydrological and bio-geochemical processes to the changes within the practices. Calibration and sensitivity analyses were satisfactory. Model calibration metrics including p-factor, r-factor, NSE, and R^2 are 0.58, 0.53, 0.74, and 0.75 respectively. Changes in fertilizer, tillage, pesticide applications, also spatial variability of landuse and soil maps were analyzed to evaluate the non-point source and point source pollution. Considering the sustainable practices used in this study, results demonstrate significant decrease in nutrient loads. Total nitrogen and total phosphorus decreased 44% and 31%, respectively. Nitrate, Ammonium, and Nitrite in streams reduced ranging from 12% to 59%. Suspended sediment also decreased 29%. Pollutants pattern follow the precipitation pattern. Soil characteristics play a major role in the nutrient losses. All these changes will decrease the risk of eutrophication and already-imperiled ecosystem degradation. The conservation practices include managing the soil for maximum water infiltration and storage, maintaining vegetation on ditch banks and in drainage channels, and conservation tillage, strip cropping, contour farming, converting agricultural area to forest, and constructed wetlands. Evaluation of the Management practices show spatial variability through the watershed. Optimization analyses is required for developing sustainable water management practices on sub-watershed scale. The results also can be used to locate the priority monitoring regions and critical monitoring period of NPS pollution endangering surface and subsurface water quality.

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Pinpointing decadal-scale “hot spots” of legacy nitrogen storage in the Chesapeake Bay watershed using differential spatially referenced regression

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Legacy nutrient storage is commonly identified as an impediment to efforts to improve regional water quality. However, quantifying the effect of legacy storage on nutrient trends in large, mixed-land-use watersheds is problematic: Capacity for terrestrial storage varies spatially with physiography (e.g. crystalline versus sedimentary lithology) and land use (e.g. forest versus row crop agriculture), as well as vertically throughout the critical zone (e.g., above-ground biomass, root-zone, groundwater). In the aquatic realm, nutrient storage can occur in flowing water, floodplains, wetlands, lakes, and reservoirs. Moreover, the effects of storage on water-quality trends may be evident at some time scales, but not at others. I used the differential spatially referenced regression model Spatiotemporal Watershed Accumulation of Net effects (SWAN; Chanat and Yang, https://doi.org/10.1029/2017WR022403) to relate 1990-2010 trends in flow-normalized flux of total nitrogen at 43 sites in the non-tidal Chesapeake Bay watershed to contemporaneous changes in sources and factors influencing terrestrial/aquatic transport. I hypothesized that potential storage “hot spots” over this time scale can be identified through any combination of significant a) interactions between changes in sources and terrestrial transport factors; b) model-intercept terms suggesting a terrestrial source (or sink) other than those explicitly specified; or c) terms indicating capacity for streams and/or reservoirs to act as sources (or sinks). Using a modified “best subsets” regression approach and an information-theoretic selection criterion, I demonstrate that the available data support several plausible model structures, underscoring the challenges associated with quantifying legacy storage in large, mixed-land-use watersheds. I conclude by suggesting the additional spatiotemporal data sets that would most effectively resolve this equifinality.

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Simulating hydrology of current stands and post-longleaf pine restoration on a coastal watershed, South Carolina

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Abstract—This study used a process-based hydrologic model, MIKE SHE, to simulate streamflow of a 155-ha, moderately well-drained watershed on loblolly pine stands (LPS) with a mean leaf area index (LAI) of 3.95 and effects of longleaf pine (LLP) (LAI = 2.0) restoration on streamflow within the Santee Experimental Forest, SC. Climatic data (2011–2019) including extreme rainfall and dry events were used for streamflow calibration for the current LPS and projection for LLP restoration scenario. Results showed "very good" calibrated model performance compared with monthly observed flow for both, with very large October events in 2015 and 2016 (R^2 = 0.96, Nash-Sutcliffe efficiency [NSE] = 0.95, PBIAS = 6.4 percent, and ratio of root mean square error to standard deviation [RSR] = 0.22) and without those two months (R^2 = 0.89, NSE = 0.82, PBIAS = 6.1 percent, and RSR = 0.42). Model simulations converting the current LPS to LLP showed a 57-mm (22.3-percent) increase in average annual streamflow, due to reduced (-58 mm) simulated canopy interception and increased throughfall translating to increase in soil evaporation (+24 mm) and decrease in transpiration (-34 mm).

INTRODUCTION

Restoration of longleaf pine (*Pinus palustris*) ecosystems is an important land management objective throughout the Southeastern United States, and it is the principal goal described in the recently approved Forest Plan for the Francis Marion National Forest (USDA Forest Service 2017). While there have been numerous studies regarding longleaf pine (LLP) ecology, silviculture, and the associated responses of ecosystem services (Samuelson and others 2012), there are major uncertainties regarding the effects of watershed-scale restoration on the hydrology and water yields. In contrast to loblolly pine (*P. taeda* L.) stands, LLP stands have much lower stocking densities with more open canopy and the understory generally dominated by grasses and sedges, potentially influencing both soil moisture and evapotranspiration (ET) (Trettin and others 2019). As a result of these differences in stand structure and composition, it may be expected that LLP stands will exhibit less interception loss, lower total tree transpiration, and more infiltration of precipitation recharging ground water (Brantley and others 2018, McLaughlin and others 2013). Powell and others (2005) observed in their study

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on a naturally regenerated coastal pine flatwood forest that understory in the open-canopy stand plays a more significant role in ecosystem hydrology because of the greater understory leaf area index (LAI) and enhanced penetration of radiation through the overstory canopy. However, the above studies have been done on a stand scale (i.e., individual trees or small field plots); hence, there is considerable uncertainty scaling those responses to a watershed, due in large part to the spatial heterogeneity of soil conditions, microtopography, and understory vegetation. Despite this, there are limited studies, to the authors' knowledge, on spatial hydrology of the LLP forests and watershed-scale effects of the LLP restoration on water yield, except for a stand-scale study on energy dynamics and ET as affected by soil types (Whelan and others 2015).

Paired watershed studies are often conducted to assess effects of silvicultural practices on water yield, other hydrologic variables (e.g., peakflow, baseflow), and ecosystem services (Bosch and Hewlett 1982, Brown and others 2005) primarily on first-order watersheds. Accordingly, a paired watershed monitoring approach is underway for quantifying both short-term effects of silvicultural treatments for restoring the LLP (Amatya and others 2021), typical of the lower Coastal Plain, and long-term effects of post-restoration on hydrology and water yield on the Santee Experimental Forest (SEF), which is located within the Francis Marion National Forest, near Charleston, SC. Since long-term monitoring is often resource restricted, we intend to use a validated ecohydrologic model to further understand process interactions and evaluate impacts of various management treatments, consistent with Lewis and others (2012), who, also, because of the difficulty of observing the long-term changes in the field, utilized a hydrologic model to simulate the rainfall runoff processes of an existing pristine blanket peatland and then to simulate the hydrology of the peatland if it were drained and afforested.

The process-based three-dimensional (3-D) MIKE SHE (DHI 2017) and process-based quasi two-dimensional (2-D) DRAINMOD (Skaggs 1978) watershed-scale hydrology models have been used to simulate the hydrology of the reference (WS80) (Dai and others 2010) and of the treatment (WS77) watersheds (Amoah and others 2013), respectively, at the SEF site. The spatially distributed MIKE SHE model, which simulates ET and saturated and unsaturated flow components for predictions of water table depth and streamflow, was found to be more satisfactory than DRAINMOD for those watersheds. The MIKE SHE model can also better represent the spatial heterogeneity of topography, soil, vegetation, and precipitation inputs (Ma and others 2016). Therefore, the objectives of this study are twofold: (a) to calibrate the MIKE SHE model on WS77 using 9 years (2011–2019) of hydro-climatic data for current conditions, and (b) to apply the model to simulate the effects of full LLP restoration of the entire watershed on water yield. This will also provide a basis to evaluate the performance of the model in predicting the water yield against the earlier modeling studies at the SEF site.

METHODS

Study Site

The treatment watershed (WS77) is a 155-ha first-order watershed that is paired with a 160-ha reference watershed (WS80) within the SEF and drains downstream to Huger Creek, an eastern tributary of Cooper River discharging to Charleston Harbor (fig. 1A). The elevations of this low-gradient watershed vary from 5.6 m (at the outlet) to 10.5 m above mean sea level with ~2-percent slope (Amoah and others 2013). Soils on the watersheds are characterized by a seasonally high water table and poorly to moderately well-drained sandy clay loam overlaying clay that are typified by the Wahee and Craven soil series in the uplands and the Bethera soil in the riparian zones (fig. 1B) (SCS 1980). The vegetation on WS77 is dominated by regenerated loblolly pine, LLP, and some bottomland hardwoods along the riparian areas (Amatya and others 2021; Trettin and others 2019). The climate in the region is warm-temperate, with an average daily temperature of 17.8 °C and average annual rainfall of 1370 mm, with about 40 percent occurring during June–August (Dai and others 2013).

Hydrologic Measurements

Rainfall data were collected using automatic tipping bucket gauges backed up by a manual gauge for verification at Met5 station on the WS77 watershed. A gauging station instrumented with stage recorders and a compound concrete V-notch weir, installed at the outlet of WS77, measured stream stage on a 15-minute interval to compute outflow rates (fig. 1) using an established rating curve (revised recently). Water table depth (WTD) was recorded on an hourly basis on recording wells (Well J) equipped with dataloggers (fig. 1). Complete weather data were collected on a 15-minute basis by a weather station installed in a tower above the forest canopy on the adjacent reference

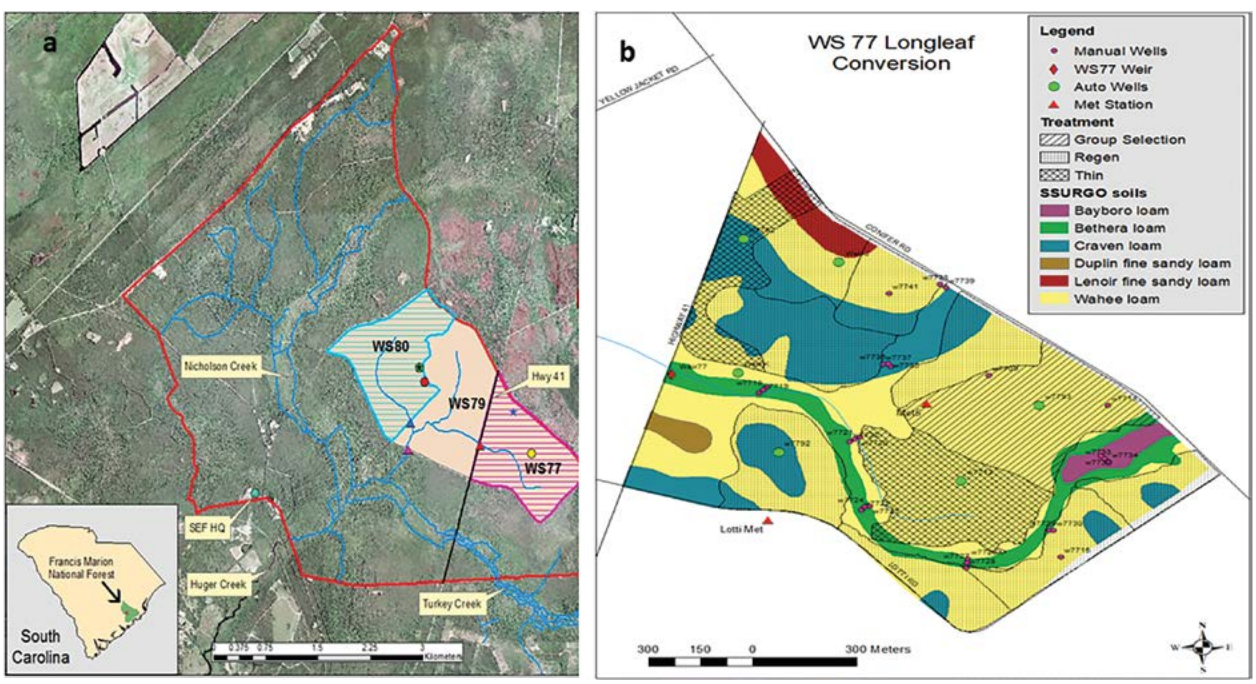


Figure 1—(a) Location map of the study watershed (WS77) in the paired system with the reference watershed (WS80) within the Santee Experimental Forest and (b) the treatment watershed (WS77) for longleaf conversion shown with locations of hydrologic monitoring stations as well as soil series and treatment types.

watershed (WS80) (fig. 1A) (Amatya and Trettin 2021). The LAI was measured on a 2–3 week basis from July 2019 to May 2020 (n = 9) at three locations of proposed treatments for regeneration, thinning, and group selection on WS77 (fig. 1B). Measured soil hydraulic properties were used as reported by Dai and others (2010) for WS80. Additional details of hydrologic monitoring procedures and other watershed characteristics have been reported elsewhere (Amatya and Trettin 2007, 2019, 2020; Dai and others 2010, 2013; Harder and others 2007). Both the historic and recent hydrology and meteorological data for the study site (WS77) can be accessed at https://www.fs.usda.gov/rds/archive/Catalog/RDS-2019-0033.

Data Analysis

Breakpoint data from automatic rain gauges were integrated to obtain the daily, monthly, and annual totals. Similarly, computed flow rates were integrated to obtain daily, monthly, and annual streamflow. Hourly WTD was aggregated to obtain daily averages. The weather data were integrated to daily averages, which were used to estimate daily potential evapotranspiration (PET) using the Penman-Monteith (Monteith 1965) method following Amatya and Harrison (2016). Daily PET was summed to obtain monthly and annual totals. The LAI data, measured in each treatment area covering current forest stands in 2019, was assumed to be the same for the whole 2011–2019 period.

MIKE SHE Model

MIKE SHE (DHI 2017) is a modularized and spatially distributed watershed hydrologic model with user-friendly graphical user interfaces to simulate the complete terrestrial water cycle, including 3-D saturated zone (SZ) water movement in soils, 2-D water movement of overland flow, one-dimensional water movement in river/streamflow, unsaturated zone (UZ) water movement, and ET. It is a flexible watershed hydrologic modeling tool applicable at spatial scales ranging from a single soil profile to large regions with several river catchments (Graham and Butts 2005), and each of the hydrologic processes can be represented at different levels of spatial distribution and complexity (Butts and others 2004). Accordingly, we chose to use a rather simple two-layer water balance method of MIKE SHE, which does not represent variation in soil properties with depth in the UZ and is an alternative to more complex processes in this UZ (DHI 2017). The main purpose of the module is to calculate actual ET and the amount of water that recharges the SZ, which is particularly useful for areas with a shallow ground water table, such as wetland areas characteristic of this poorly drained coastal study site, where the actual ET rate is close to the reference rate. The method assumes one or two layers in the UZ, depending upon the water table position.

The ET is modeled as a function of PET, LAI, and root zone soil moisture content. The model has been applied to hydrologic processes in humid Southeastern U.S. forest ecosystems and semi-arid regions (Dai and others 2010, Gibson and others 2020, Lu and others 2009, Zhang and Ross 2015). The model was parameterized according to the guidelines established in the MIKE SHE manual (DHI 2017). The spatial input data include topography (e.g., Digital Elevation Model [DEM]) using high-resolution Light Detection and Ranging (“LIDAR”) data (Photo Science 2007), Soil Survey Geographic Database (SSURGO) soil types (USDA NRCS 2018), land use-land cover types (SCDNR 2020), in situ-measured LAI and temporal data on measured daily precipitation from the aforementioned Met5 station, and uniformly distributed daily Penman-Monteith PET described above. Saturated flow in MIKE SHE was modeled using the 3-D Finite Difference Method. Drainage to the streams is calculated by tracking the ground water table levels in the soil cells adjacent to surface water in the stream network (DHI 2017) and is eventually routed to the outlet of the watershed.

Model Calibration and Input Parameters

The model simulation run was conducted with 9 years (2011–2019) of climatic data, with 2 prior years (2009–2010) as a "warm-up" period not used for analysis, to primarily calibrate the monthly streamflow (water yield) with the observed data. Manual calibration was performed by running multiple simulations by changing parameters that were reported to be sensitive to water yield in an earlier study by Dai and others (2010) for the adjacent WS80 watershed. Those parameters included root depth, ET surface or extinction depth (sum of the root depth and the thickness of capillary fringe), surface detention storage, Manning parameter, drain depth, and soil moisture content at the vegetation wilting point and saturated hydraulic conductivity. Results of each simulation were evaluated using both the graphical plots of observed and predicted daily, monthly, and annual streamflow data as well as statistical model performance criteria. The performance criteria used were three statistical parameters, Nash-Sutcliffe efficiency (NSE) coefficient, mean annual and monthly percent bias (PBIAS), and the root mean square error to the standard deviation (RSR) of the measured data following the Moriasi and others (2007) calibration guidelines. Graphical comparisons also included regression plots with coefficient of determination (R^2).

The key model input parameters based on final calibration are given in table 1. After final calibration, the model was

Table 1—MIKE SHE model input parameters used for streamflow calibration

Parameter	Current	Future
Vegetation leaf area index (range)	2.8–5.0 (3.95)	2.0
Root depth, mm	500	400
Manning number, $m^{(1/3)/s}$	40	40
Detention storage, mm	0–260	0–260
Canopy interception, mm	0.10	0.10
Evapotranspiration surface depth, m	0.65	0.65
Soil properties		
Saturation water content	0.418–0.496	0.418–0.496
Field capacity	0.384–0.464	0.384–0.464
Wilting point	0.20	0.20
Saturated hydraulic, m/sec	0.0002–0.0009	0.0002–0.0009
Aquifer level, m	-2.50	-2.50
Specific storage, /m	0.0008	0.0008
Drainage level, m	-0.40	-0.40

rerun to simulate a scenario of full mature LLP restoration using the same 9 years of climatic data. This scenario was created by reducing the existing average LAI of 3.95 by nearly half to 2.0 for the whole watershed (table 1), which is consistent with published LAI data for mature LLP stands (Ford and others 2008; Qi and others 2022). We also slightly reduced the rooting depth from 500 mm for the current loblolly-dominated stands with relatively dense understory to 400 mm (table 1) for substantially reduced understory generally maintained by prescribed burning in every 2- to 3-year cycle. Accordingly, the daily forest Penman-Monteith PET was also reduced by using the weighted PET for 40-percent forest and 60-percent understory for the LLP scenario. The simulated mean annual ET components of canopy evaporation, soil evaporation, and transpiration from the unsaturated and saturated zone were examined to evaluate the effects of LLP restoration on those ET components and ultimately the water yield.

RESULTS

Annual Water Balance Components

The mean annual rainfall of 1496 mm for the 9-year study period (table 2) was higher than the long-term average of 1370 mm for the study site (Dai and others 2013). This was because 6 of the 9 years (2013 and 2015–2019) yielded above-average rainfall with 2011 and 2012 yielding much lower rainfall than normal.

The annual flow was overpredicted by as much as 47 percent (84 mm predicted versus 58 mm measured) in 2011 with the lowest annual rainfall and underpredicted by as much as 48 percent (29 mm predicted versus 56 mm measured) in the subsequent year 2012, which also had below-normal annual rainfall. In general, the model overpredicted streamflow in 6 years and underpredicted in 3 years with a bias of 6.2-percent overprediction (table 2). The predicted annual runoff coefficient (ROC) varied from 2.5 percent (measured 4.9 percent) in 2012

Table 2—Measured annual rainfall and streamflow and simulated water balance components

Year	Measured rainfall	Annual streamflow		Annual error	MIKE SHE simulated				
		Measured	Predicted		Canopy evaporation	Transpiration	Soil/litter evaporation	Total evapo-transpiration	Potential evapo-transpiration
	mm	*mm*	*mm*		*mm*	*mm*	*mm*	*mm*	*mm*
2011	974.5	57.5	84.4	46.8	203.2	742.5	40.8	986.5	1351
2012	1148.0	55.7	29.0	-48.0	252.8	703.4	70.0	1026.2	1239
2013	1502.5	334.4	460.0	37.6	229.4	515.7	251.8	996.9	1017
2014	1340.5	293.1	343.7	17.3	202.5	581.9	180.4	964.8	1123
2015	2146.5	949.9	1006.3	5.9	240.6	622.1	196.6	1059.3	1098
2016	1708.7	633.1	643.8	1.7	228.4	647.9	221.0	1097.3	1197
2017	1555.1	391.9	392.6	0.2	226.8	630.7	296.4	1153.9	1177
2018	1660.9	474.1	469.0	-1.1	283.1	633.8	202.3	1119.1	1146
2019	1428.9	333.6	318.9	-4.4	215.6	767.7	108.5	1091.8	1200
Average	**1496.2**	**391.5**	**416.4**	**6.2**	**231.4**	**649.5**	**174.2**	**1055.1**	**1172**

with much drier antecedent conditions in 2011 to 46.9 percent (measured 44.3 percent) in 2015 with an extreme flow event (609 mm of measured flow) in October (Amatya and others 2016), with an average of 25.3 percent, which was 1.6 percent higher than the mean annual observed (23.7 percent) ROC. The predicted annual flow was highly correlated ($R^2 = 0.98$) with measured data with a significant ($p < 0.0001$) but biased slope of 0.94.

Simulated canopy evaporation from intercepted precipitation varied from 202 mm to 283 mm, with an average of 231 mm, which was 16 percent of the mean annual precipitation. This was higher than the storm event-based interception of 11 percent reported by Harder and others (2007) for the adjacent pine hardwood mixed forest watershed but consistent with other studies on managed pine forests in coastal North Carolina (Amatya and others 1996, Sun and others 2010) and lower than that reported by Domec and others (2012). The simulated mean annual transpiration (650 mm) and soil/litter evaporation (174 mm), which were 46 and 11 percent (57 percent combined) of annual precipitation, respectively, were slightly higher than the 53 percent reported by Amatya and others (1996). The 11-percent mean soil evaporation, which was higher than the 9 percent obtained by Domec and others (2012) for a managed pine forest with an LAI range of 3.1–5.4, may be justified by its somewhat lower LAI (table 2). The simulated mean annual transpiration was 46 percent of the annual rainfall and about 62 percent of the total ET (1055 mm) (table 2), which was somewhat lower than the 70 percent of eddy covariance-based ecosystem ET reported by Domec and others (2012) for a managed coastal pine forest. This was likely attributed to both the lower LAI as well as shallower rooting depth of the study site (table 1) compared to the LAI range of 3.1–5.4 and root depth of 1.9 m reported by Domec and others (2012) for their site. The simulated annual total ET varied from 965 mm in 2014 with just-below-average rainfall (1340 mm) to 1154 mm in 2017 with above-average rainfall (1555 mm) (table 2). As a result, the total ET (965 mm) in 2014 was well below the PET of 1123 mm compared to the 2017 total ET (1154 mm) which was near the annual PET of 1177 mm. Similarly, the years 2011 to 2014 with below-average rainfall (except for 2013 with above average rainfall and also spring prescribed burning) also yielded total ET below 1000 mm as opposed to above 1050 mm for the years 2015 to 2019 with above-average rainfall (table 2). However, both the simulated annual total ET ($R^2 = 0.23$, $p = 0.19$) and annual sum of transpiration and soil evaporation ($R^2 = 0.14$, $p = 0.23$) were poorly correlated with annual rainfall, indicating that the annual ET may have been affected by other factors like seasonal antecedent moisture besides the rainfall at this study site.

Monthly Streamflow (Water Yield)

The predicted and measured monthly water yield for the 2011–2019 calibration period is shown in figure 2. The model's predictions were able to closely follow the measured flow for most of the months, including for October of 2015 and 2016, which were impacted by large rainfall amounts due to an indirect effect of Hurricane Joaquin on October 3–4, 2015 and flooding from Hurricane Matthew on October 8, 2016. Unfortunately, some of the measured stage data for these two large events exceeded the rating curves. Data for the extremely large

October 2015 event were estimated the same as for the adjacent watershed WS80 (Amatya and others 2016). Data for the second large event of October 2016 were estimated assuming the flow rate at maximum rating curve for few hours of missing stage values exceeding the curve capacity, causing some measurement uncertainties in these two large event flows (Amatya and Trettin 2021; Amatya and others 2021).

Interestingly, the model underpredicted the April–June (the start of growing season) monthly flows in 2012, 2015, and 2017–2019. This was attributed to likely discrepancies in field soil water properties that were used from the adjacent WS80 (Dai and others 2010) resulting in deeper predicted water table depths (fig. 3). Overall, on an average annual basis, the mean monthly prediction error varied from -1.3-mm underprediction in 2019 to 10.5-mm overprediction in 2013, with a mean monthly overprediction of 2.1 mm. The 2013 overprediction was likely biased by a single month in February (fig. 2) preceded by long dry antecedent conditions since the fall of 2011 when the measured flow value was 60 mm compared to the predicted value of 108 mm as a response to 225 mm of rain. This tends to indicate the inability of the model to accurately predict flow for such dry antecedent conditions, consistent with other

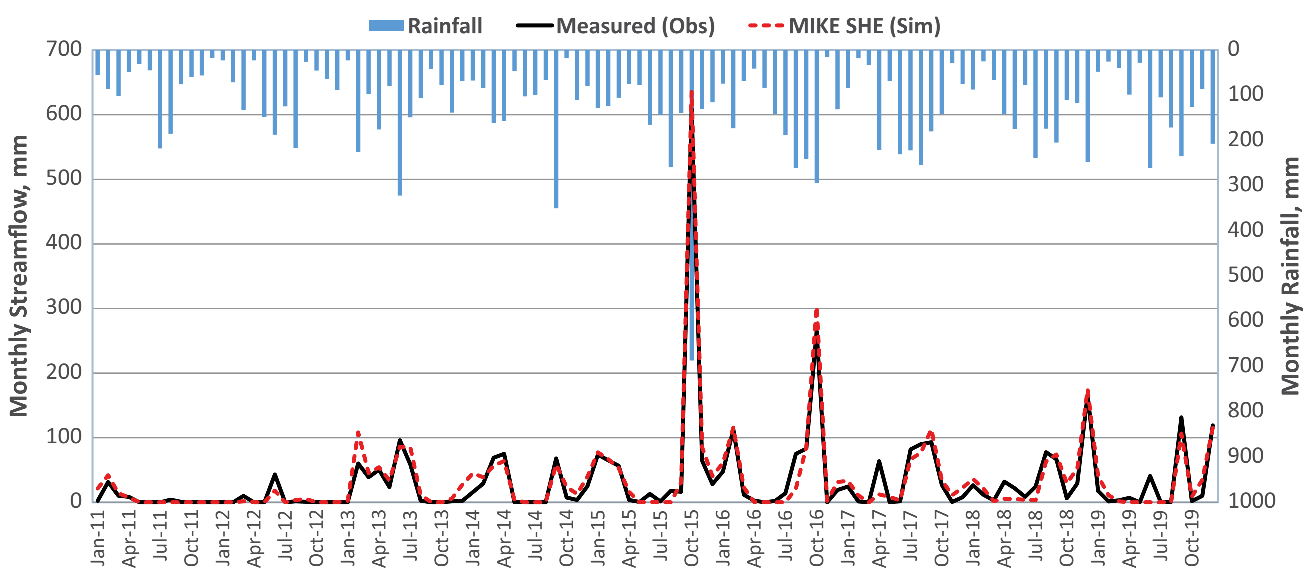


Figure 2—MIKE SHE predicted and measured monthly streamflow for the 2011–2019 calibration period for WS77 watershed.

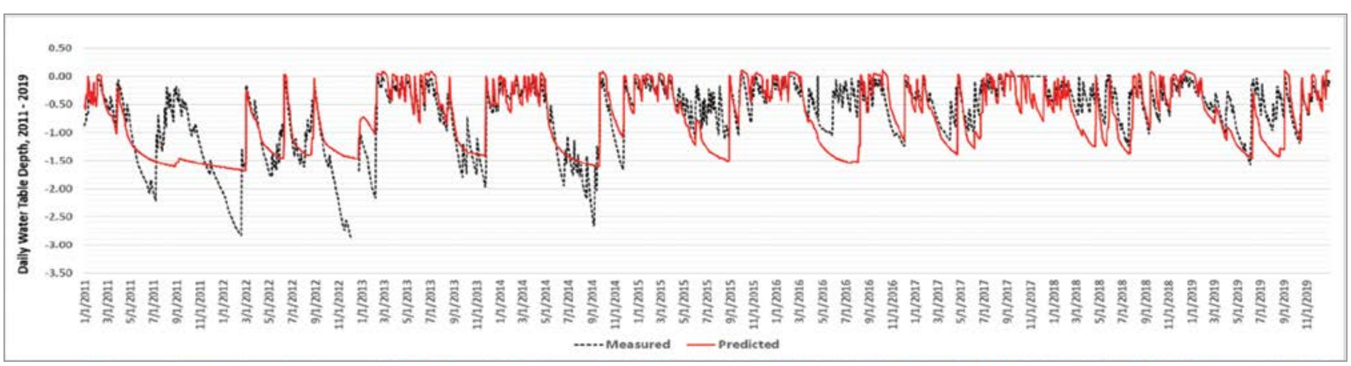


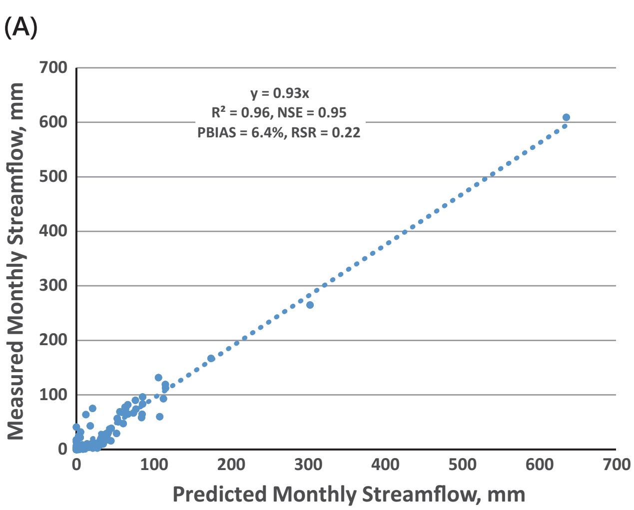
Figure 3—MIKE SHE predicted and measured daily water table depths for Well J for 2011–2019.

similar studies for simulating streamflow and water table (Amatya and Skaggs 2001, Dai and others 2010, Gibson and others 2020). One of the possible reasons is due to lack of reliable soil hydraulic properties (Hawtree and others 2015, Skaggs and others 2019).

The relationship between the predicted and monthly flow was very strong with $R^2 = 0.96$, NSE = 0.95, PBIAS = 6.4 percent, and RSR = 0.22 (fig. 4A), satisfying a “very good” model performance criterion following the Moriasi and others (2007) model evaluation guideline. However, this high degree of correlation may have been biased by a single extreme value of 609 mm measured in October 2015. Removing this as well as October 2016 data, the R^2 and NSE dropped to 0.89 and 0.82, respectively (fig. 4B), PBIAS reduced to 6.1 percent, and RSR increased to 0.42, all of which still are within the “very good” performance criterion. In both cases, the slope was also significant ($p < 0.0001$), indicating that the model can potentially be used to evaluate the effects of land cover change into LLP on seasonal and annual water yield. Our computed NSE statistics are also comparable to the values (0.84–0.98) obtained by Dai and others (2010) for MIKE SHE-based monthly flow predictions for the adjacent reference watershed (WS80).

Daily Water Table Depths (WTD)

The predicted daily WTD for an upland Well J (fig. 1) generally tended to follow the measured data fairly well for depths of about 1 m or less, except for the late spring and summers of 2015, 2016, 2018, and 2019 when the predicted depths were deeper than the measured (fig. 3). It was opposite in summer periods of 2012–2014 when measured WTD were deeper than the predicted. The model performed very poorly with almost no response in the summer of 2011. In addition, since the objective of this paper was calibrating the model for water yield, minimal effort was placed in calibrating these single well WTD data for this study. Overall, the WTD predictions were judged unsatisfactory based on mean annual bias of 5.4 cm (28 cm [2012] to -22 cm [2016]), NSE = 0.45, and RSR = 0.74, although PBIAS was just below 10 percent. These poor predictions were likely due to lack of calibration with field-measured



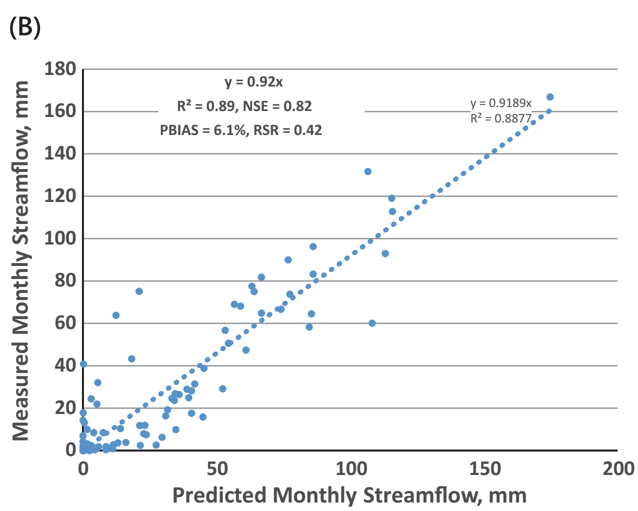


Figure 4—Regression of monthly MIKE SHE predicted and measured streamflow (A) with all months and (B) without the extreme flow months of October 2015 and October 2016.

soil hydraulic properties that were directly borrowed from the earlier study (Dai and others 2010) for the adjacent WS80 watershed (fig. 1).

Simulated Annual Streamflow for Longleaf Pine Restoration Scenario

Simulated annual water yield for current stand conditions and restored LLP scenario with the LAI reduced by half is presented in figure 5 for the same 2011–2019 period. As a result of the reduced LAI and PET, the water yield increased in all years, except in the driest year of 2011 with rainfall of 974 mm. The annual increase in 7 years varied from 22.7 mm in 2013 to 135.4 mm in 2018, with an average increase of 57 mm (or 22.3 percent), compared to 17.9 mm (or 5.2 percent) average increase in water yield by converting 95000 ha of forest to LLP forest in Flint River Basin in Georgia (Qi and others 2022).

A closer examination of simulated components of mean total ET are shown in figure 6 as canopy evaporation (Can_E), unsaturated (UZ_T) and saturated (SZ_T) zone transpiration, total transpiration from both the zones (Tot_T), soil-water evaporation (SW_E), and total ET (Tot_ET) as sum of the Can_E, Tot_T, and SW_E. Clearly, as a result of reduced LAI, mean Can_E was reduced by 58 mm with a 6-mm reduction in SZ_T possibly caused both by reduction in PET and root depth. While the total transpiration was reduced by 34 mm, the 24-mm increase in SW_E due to reduced LAI resulted in a net reduction of total ET by just 68 mm, on average. These results showed that with the current climate conditions, this average reduction in watershed-scale annual ET was the cause for a 22.3-percent, on average, increase in annual water yield shown above for conversion into the LLP stands. It will be interesting to examine, however, the response of the system to water yield when future climate projections will be used to simulate the hydrology of the LLP restoration.

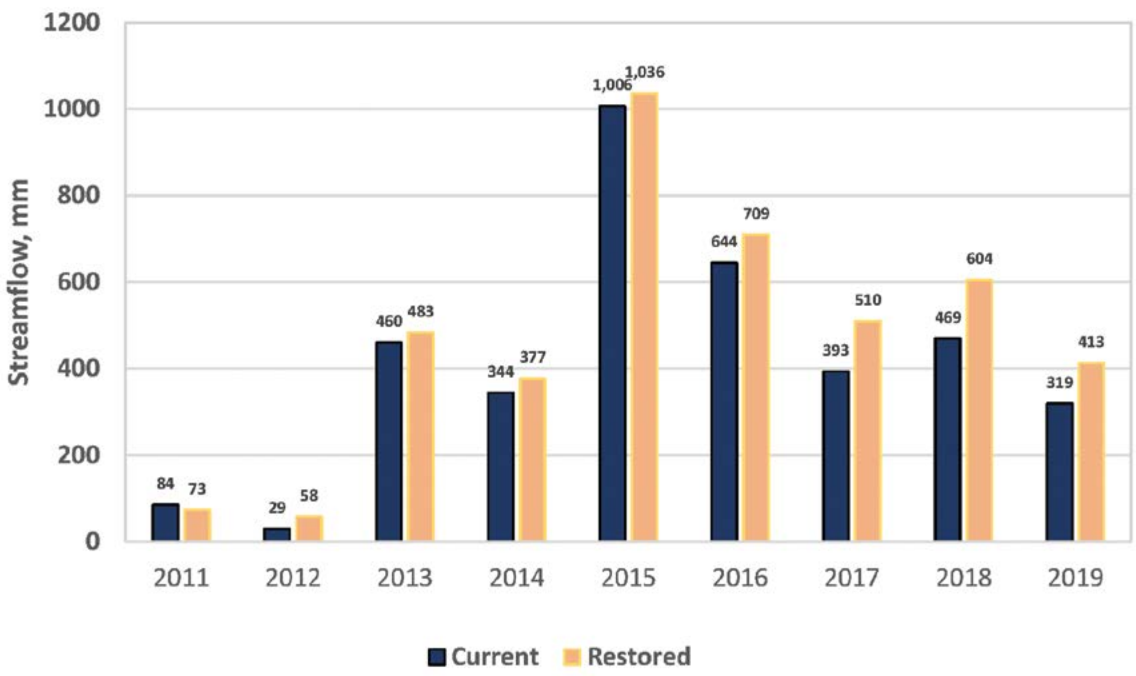


Figure 5—Simulated annual water yield for current stand conditions and longleaf pine restoration scenario for the same 2011–2019 climatic conditions on watershed WS77.

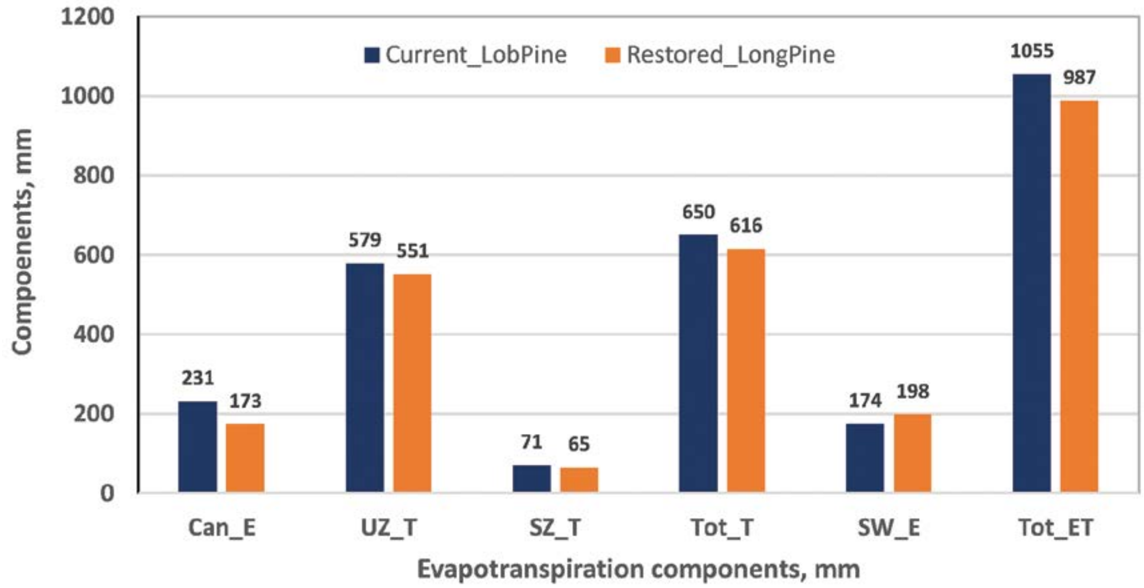


Figure 6—Simulated annual evapotranspiration components (Can_E = canopy evaporation; UZ_T = transpiration from unsaturated zone; SZ_T = transpiration from saturated zone; Tot_T = total transpiration; SW_E = soil-water evaporation; Tot_ET = total evapotranspiration) for current stand conditions dominated by loblolly pine stands and longleaf pine restoration scenario for the same 2011–2019 climatic conditions.

SUMMARY

MIKE SHE slightly overpredicted measured average seasonal and annual flow for the 155-ha forested watershed on the shallow water table coastal site. However, the model performance was found to be "very good" based on recommended evaluation criteria, even when two October months of 2015 and 2016 yielding very large flows with some data uncertainty were excluded. The simulated annual ET and its components are reasonable when compared to published data for managed coastal pine forests. Results also showed that the simulated annual ET may have been affected by seasonal antecedent moisture besides the rainfall. However, its ability to predict daily water table depth as a surrogate of soil moisture at a single location was found to be rather poor, as expected. This was attributed primarily to the limited model calibration with field data on soil hydraulic properties that were lacking for heterogeneous soils across the watershed (Hawtree and others 2015) followed by microtopography (e.g., depressional storage) (Koch and others 2016). Lack of field calibrations may also lead to some biased opinions of hydrologic processes in a catchment scale (Liu and others 2016).

Simulation results with current climate for the LLP scenario yielded reduced canopy evaporation and increased throughfall, resulting in a 22.3-percent (57-mm) increase, on average, in water yield for a 68-mm decrease in simulated total ET based on minimal field calibration. Thus, this study suggests a need to realistically parameterize the model for the LLP scenario for the LAI, rooting depth, and PET as well as obtain measurements of actual ET of LLP forest ecosystems to validate the hydrologic response to restoration. In addition, future studies using the validated model should also evaluate the LLP restoration effects on water yield on a broader landscape and using the projected climatic data from global circulation models applicable to the Southeast.

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Development of Regional Streamflow Duration Assessment Methods (SDAMs) for the United States

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Regulators and regulated entities need rapid, reach-scale methods to classify streamflow duration to implement and comply with many federal, state and local programs. For example, streamflow duration tools are needed to help make determinations of jurisdictional waters under the Clean Water Act, identify regulated waters under other statutes, inform compensatory mitigation requirements, or to appropriately apply water quality standards. We are developing rapid field assessment methods that use hydrological, geomorphological, and/or biological indicators, observable in a single site visit to classify stream reaches as perennial, intermittent or ephemeral. The objective of this effort is to test and adapt existing streamflow duration assessment methods (SDAMs) and field indicators to develop regional methods for the Arid Southwest (ASW), Western Mountains (WM), Great Plains (GP), Northeast and Southeast. A protocol that includes 32 field indicators derived from methods currently used in the Pacific Northwest and New Mexico was performed at 100 reaches in the ASW, 51 reaches in the WM and 180 reaches in the GP.

Validation of SDAMs requires study reaches with known flow duration classes. Existing hydrologic data (e.g. USGS gages) and regional expert knowledge were used to classify streams as perennial, intermittent, or ephemeral at all sites. In addition, Stream Temperature, Intermittency and Conductivity loggers were placed at sites in the WM and GP to characterize flow duration for one year. Interagency collaboration is welcome to help identify study sites in the Northeast and Southeast and to provide technical recommendations and field testing of methods throughout the method development process in all regions.

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Agricultural Greenhouse Gas Emissions in Response to Climate Change: A Basin Scale Modeling Approach

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Climate change leads to higher surface temperature and more fluctuated precipitation, which will affect agricultural production, soil greenhouse gas (GHG) emission as well as other environmental factors. Considering this changing climate, optimization of agricultural system with minimal GHGs and reasonable production has become very crucial. The objective of this study is to find the best agricultural management options in terms of grain productions and major GHG emissions in response to the current and projected future climatic scenarios. The tool used for the analysis is process based DNDC (Denitrification & Decomposition) model. The model takes the soil-climatic and cropping management inputs to determine the soil-substrates condition; which is then followed by the estimation of grain production and GHG emissions by denitrification, nitrification and decomposition sub-models. For the model input, ten GIS database are prepared to be superimposed by 147 sub-watershed grids to account for the spatial variations in soil-climatic components. The tested management options are consisted with various types of tillage, manures, residue incorporations and crop rotations for the major crops (Cotton, Peanut, Corn and Soybean) of the Choctawhatchee watershed. The future climatic scenarios are generated using change factor methodology on projected temperatures and precipitations of two timelines (2006-2035 and 2070-2099). To calculate the overall emissions, the term Global Warming Potential (GWP) is introduced which is the summation of all GHGs as CO_2-equivalents. The GWPs for each hector of land and unit grain production are determined to compare the net benefit (NB) from each scenario. For the existing cropping systems, the lowest GWPs as well as the highest Net Benefits (NBs) are seen to be associated with different amount of manure amendments from the model outputs. The long term model runs have also shown higher carbon sequestration potential (CSP) as well as soil productivity with the incorporation of manures (76%-247%), no-till (26%-64%) and crop rotations (17.5%-38%). Thus, these results can be helpful to choose most effective agricultural management scenarios with better impacts on emissions, CSPs, grain yields and NBs in response to climate change.

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Section 15: Long-Term Agroecosystem Research

Cropping patterns over two decades in the Little River Experimental Watershed, Georgia, USA

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INTRODUCTION

The Little River Experimental Watershed (LREW) is at the center of the Gulf Atlantic Coastal Plain (GACP) Long-Term Agroecosystem Research (LTAR) Network site (Walbridge and Shafer 2011). A goal of the LTAR Network is to conduct research and gather observations on agricultural practices with the goal of promoting the sustainable intensification of agriculture (Kleinman and others 2018). To achieve this goal, a common experimental framework compares a “business-as-usual” (BAU) baseline with new “aspirational” management systems (Spiegal and others 2018). In agricultural regions like the GACP, where cropping systems predominate, the BAU system baseline can be defined by examining cropping characteristics, including types, proportions, and frequencies. This research assessed cropping patterns in the LREW to better understand the characteristics of BAU for the GACP LTAR site.

To characterize cropping systems, annual maps of crop type are required like the Cropland Data Layer (CDL), produced by the U.S. Department of Agriculture National Agricultural Statistics Service (UDSA-NASS) (Boryan and others 2011) using medium resolution satellite imagery. While this data product is indispensable for mapping national/regional cropping systems, there are limits to the utility of the dataset for mapping temporal trends and small areas (Lark and others 2017), and independent crop type datasets are needed to verify and assess the accuracy of the CDL. Here, we summarized data from an annual crop survey in the LREW and used it to assess the accuracy of the CDL. We also explored the relationship between field size and crop type accuracy in the CDL using crop field boundaries digitized from aerial photography for the LREW and surrounding area.

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METHODS

The LREW basin is a 334-km^2 watershed in Georgia, covering portions of Tift, Worth, and Turner Counties (Bosch and others 2020, Bosch and others 2006). The predominantly rural landscape comprises riparian and production forests, crop fields and pastures, where field sizes tend to be relatively small and field shapes are irregular. Since 1997, researchers at the LREW have been recording crop type observations for a set of fields throughout the watershed (Bosch and others 2007), and providing ground truth for crop type classifications (e.g., Dingle Robertson and others 2020, Huang and others 2021, Whitcomb and others 2020). These LREW "windshield surveys" now occur twice yearly, in August and February, corresponding to summer and winter growing seasons.

To accomplish this analysis, we digitized both the observational data from 20+ years of summer windshield surveys, and the boundaries of 11,000+ crop fields visible in aerial photography from 2015 USDA aerial imagery (U.S. Department of Agriculture 2015) of the three intersecting counties. The field boundaries were used to calculate the majority crop type for those areas from the CDL for 2016 through 2019. We used a geographic information system to summarize and compare the survey data with the CDL mapped data layers.

The LREW windshield survey consists of data from 1997 to 2019, with gaps in 2009, 2010, and 2015 (fig. 1). The survey has been expanded three times – in 2001, 2007, and 2016 – creating four groups of comparable datasets by multiple observers.

RESULTS

Over the 20-year period, the number of fields surveyed increased (table 1) along with the number of land cover types as observations became more specific. Despite these differences, the proportions of major BAU commodities—corn, cotton, and peanuts—could be tabulated. Throughout the period, cotton was the dominant crop throughout the survey fields, while corn was the least common. Occurrences of peanut fields were more variable, often swapping places with "other crops," even on an annual basis.

The CDL data for the tri-county region showed similar proportions as the LREW survey fields. In survey years 2016–2019, cotton was grown in 50–60 percent of fields, and the proportion of corn remained at or below 5 percent. Peanut was grown in about

Table 1—Data summary from the 1997–2019 Southeast Watershed Research Laboratory's summer windshield survey

Survey years	No. of records per year	No. land cover types per year	Percent corn	Percent cotton	Percent peanut	Percent other crops
1997–2003	292–343	11–15	1.6	44	20	26
2004–2006	328	14–16	2.0	43	24	17
2007–2014	508–529	18–27	2.7	47	13	21
2016–2019	586	22–26	3.6	43	19	20

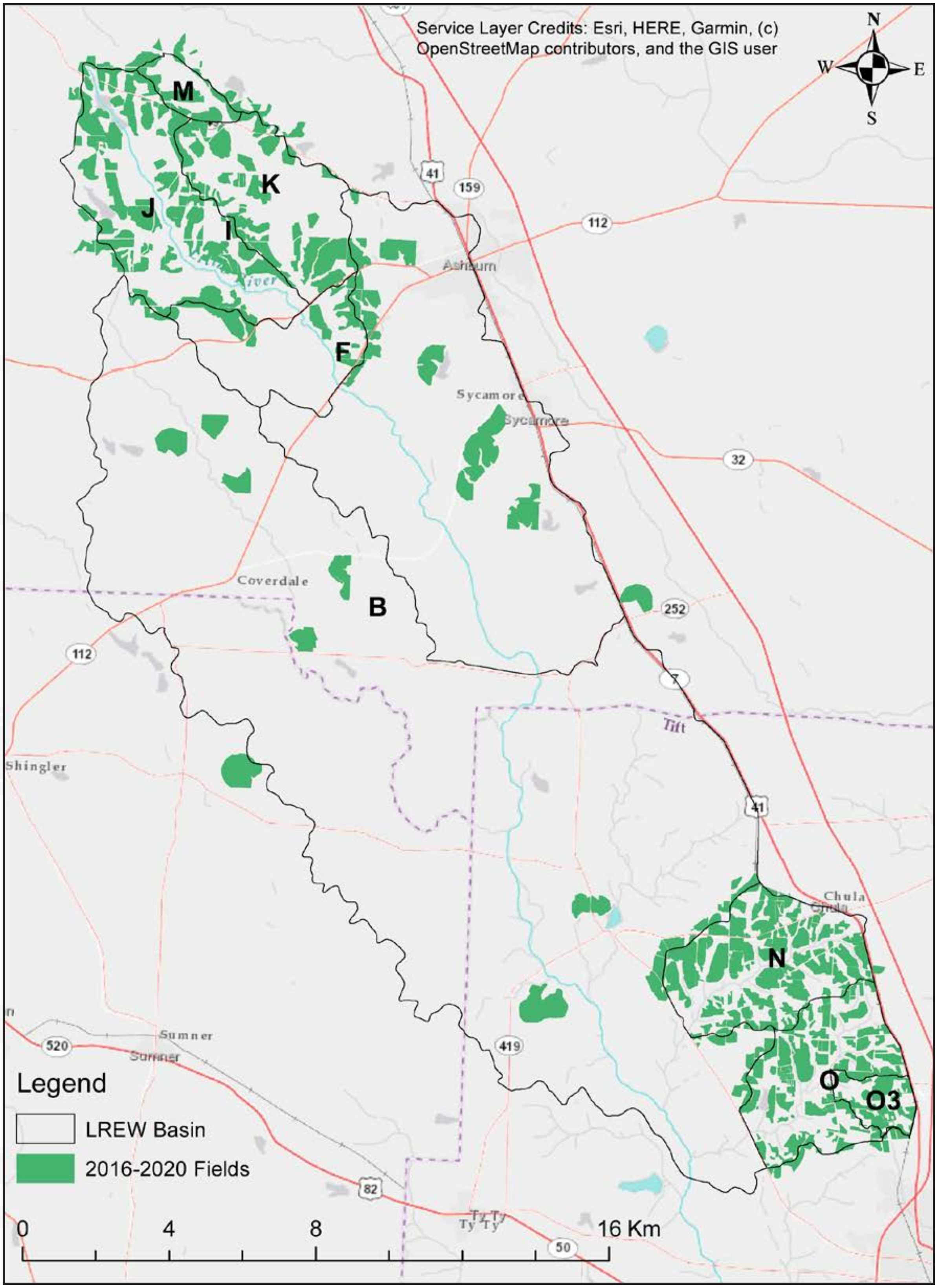

Figure 1—Map of the 2019 Southeast Watershed Research Laboratory's summer windshield survey.

23 percent of the fields, while other crops occurred in 10–20 percent. The similarities of these datasets apparently confirm the general use of the CDL to ascertain trends of cropping patterns for the region.

The accuracy assessment of the CDL determined how often the LREW survey data were classified correctly in the CDL, otherwise known as "producer's accuracy" (Lillesand and others 2004). The most recent LREW survey data were compared with the CDL classifications for corn, cotton, and peanuts, where the CDL crop type was calculated as the majority of pixels within the field boundary. Cotton was consistently classified correctly, with 97–99 percent of the survey fields classified correctly in the CDL. However, corn and peanuts fared less well, with accuracy levels of 11–66 percent for corn, and 45–80 percent for peanuts.

The CDL data are provided with a 30-m pixel resolution, exceptionally fine for continental scale. However, even at this resolution, small irregularly shaped objects are poorly discerned, leading to high classification errors for these small entities. This is a problem for regions like south-central Georgia where small fields predominate. The average size of correctly classified fields in the LREW survey was 8.75–12.5 ha, while incorrectly classified fields averaged 4.5–6.8 ha. However, of the 11,000 crop fields in the tri-county region, 50 percent of the fields were < 5 ha. While the majority (86 percent) of the cropped area consists of fields > 5 ha, small fields constitute the greatest number and a significant proportion (14 percent) of the land area. Perhaps more importantly, each small field represents an agricultural management choice, which is likely to be poorly observed in the CDL.

CONCLUSIONS

Crop types in the LREW basin follow similar cropping patterns as described in the CDL for the surrounding area. However, small field sizes and irregular configurations, which dominate the landscape, pose a challenge to relying on the CDL for evaluating crop types in the region. It is likely that a higher spatial resolution in the land cover classification source imagery could improve classification accuracies, thereby improving our understanding for what constitutes "business-as-usual" cropping patterns in the region.

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Characterizing transport of natural and anthropogenic constituents in a long-term agricultural watershed in the northeastern U.S.

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As recent technologies enable water samples to be collected at increasingly shorter time intervals, water quality data can more fully capture the range of conditions a stream experiences over time. Various metrics can be employed with the large, high-temporal resolution (i.e., sub-daily) data sets to gain insights into the hydroclimatic and biogeochemical processes affecting chemical fate and transport. These insights can be helpful in understanding the extent to which anthropogenic activities have impacted the natural response of some constituents, such as nutrients and salts, in managed landscapes. Here, nearly four years (12544 samples from 2015 to 2019) of water quality data for twelve constituents of interest were collected using three sampling strategies: (i) three times per week; (ii) high-temporal resolution flow-paced sampling to capture stormflow; and (iii) time-paced sampling with a time interval of 4 hours. Seasonal trends were investigated to understand concentration variability over time and concentration-discharge (C-Q) relationships were developed to categorize the transport dynamics of each constituent. Lorenz curves and Gini coefficients were employed to quantify the temporal inequality of the constituent loads discharged at the watershed outlet and understand the extent to which the transport behavior of geogenic constituents and those affected by anthropogenic activities differed. Overall, the results suggested that nearly all of the geogenic constituents, plus NO_3-N and SO_4-S, exhibited chemostatic dynamics with loads overwhelmingly controlled by flow variability, whereas Al, Fe, NO_2-N, and PO_4-P exhibited episodic transport dynamics that were likely controlled by source availability. Since the transport of NO_3-N was found to be similar to the transport of common geogenic constituents for the region, this suggests that decades of agricultural activities in the watershed have led to the emergence of legacy nitrogen sources, while the episodic dynamics observed for PO_4-P suggest that best management practices appear to have prevented the emergence of phosphorus legacy sources.

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Dissolved organic matter in agricultural watersheds: Spatial and temporal variability across the LTAR network

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Carbon cycling is a critical process in agricultural systems and its accurate quantification is essential for designing effective land management policies. Dissolved organic matter (DOM) represents a large component of the carbon pool in aquatic systems and agricultural practices have been shown to alter its amount, composition and bioavailability. However, the spatial and temporal relationships between DOM composition and land management practices have not been elucidated for agricultural watersheds. Therefore, we studied the variability in DOM quality of water samples collected from 14 Long-Term Agroecosystem Research (LTAR) network sites with different land use under cropland, pastureland and rangeland management. For DOM characterization, dissolved organic carbon (DOC) and total dissolved nitrogen (TDN, NO_3-N, and NH_4-N) concentration, in addition to analysis of UV-visible absorbance and fluorescence spectra were measured. Characterization of DOM was also performed by combining excitation-emission matrix fluorescence with parallel factor analysis (EEM-PARAFAC). There was a large range in both concentration and quality of the DOM, with the DOC concentration ranging from 4 to 50 mg DOC/L and the TDN concentration ranging from 0.1 to 10 mg TDN/L. The ranges in specific UV absorbance and DOM molecular weight suggest variations in DOM composition within a specific study area, and with respect to both spatial and temporal scales. The data presented emphasize that optical properties of DOM can be highly variable and influenced by environmental processes as well as land management practices. Results from this LTAR cross-site study indicate that DOM optical measurements may provide a greater understanding of organic matter dynamics and structural influences associated with nutrient and contaminant fate and transport in agroecosystems.

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Southern Plains LTAR Agroecosystem Research

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The Southern Plains (SP) Long-term Agroecosystem Research (LTAR) site is engaged in "watershed" research at three scales: small scale (1.5 ha), production scale (Avg = 6.5 ha), and medium scale (610 and 787 km^2). Each of these watersheds will be described in terms of physical characteristics, instrumentation deployed, experimental design, their purpose, and, where appropriate, findings relative to the research goals of LTAR.

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Use of a simulation model for increasing agroecosystems sustainability

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Maize yield can be affected by numerous factors and because every field is different, increasing maize yield across all environments is not easy. It is crucial to implement a proper soil fertility program that will be the foundation for achieving high yields. Nitrogen (N), phosphorous (P), potassium (K), and micronutrients should be applied at the right time and right amounts to ensure no in-season deficiencies arise. Moreover, tillage method, planting date, population, and proper rotation are factors that can keep yields consistently high. Crop simulation models are one of the technologies behind precision agriculture that can assist in taking proper management decisions. In this three-year study the objectives were to measure the agronomic response of maize to high yield management practices and use crop simulation models to evaluate additional management scenarios. The main goal of this study was to determine the effect of high fertility management strategies on maize in Georgia. Two treatments regarding high fertilization rates were tested in a 1.78 ha field, located in Tifton, GA. Conventional management practices were implemented during the first year of the project while intensive ones were implemented the following two years. Soil samples were collected before and after each growing season, while tissue samples were collected during multiple growing stages from V3 to R4. The field data are being used for calibrating and evaluating the DSSAT CERES Maize model. The model is being used to conduct sensitivity analyses to identify the limiting factors in maize production and inform Georgia growers on how to sustainably intensify maize production.

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Using remote sensing and deep learning to assess regional boundaries of the Gulf Atlantic Coastal Plain long-term agroecosystem research network site

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Studying long-term agricultural trends is crucial for understanding the future of food security in response to increasing global population, climatic variations, and economic demand. The U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) currently operates the Long-Term Agroecosystem Research (LTAR) Network to research the sustainable intensification of agriculture in the conterminous United States. The network includes the Gulf Atlantic Coastal Plain (GACP) LTAR site, a region spanning across south Georgia and into both Florida and South Carolina within the Southeastern Coastal Plains. The GACP is managed by the ARS Southeast Watershed Research Laboratory in Tifton, GA, where scientists have been observing cropping, hydrologic, and climatic systems in the 334-km^2 Little River Experimental Watershed since 1968. This study aims to integrate remotely sensed data acquired by satellites, aircraft, and small unmanned aerial systems (UAS) with field-based measurements to better understand how well the greater Coastal Plain area is represented by measurements within the GACP boundary. Using this approach, we will use remotely sensed data and climate variables to derive vegetation indices, crop cover classifications, and indicators of ecosystem services at field, landscape, and regional scales. We will characterize landscape structure and processes operating within the GACP with the goal of identifying appropriate scaling methods for the extrapolation of agricultural research results, using statistical methods to identify, validate, and guide the improvement of scaling models. The Coastal Plain region will be evaluated in terms of its representativeness of GACP research results to identify realistic boundaries for the inference of results. To accomplish this, we are exploring statistical and deep learning

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methods, such as convolutional neural networks (CNNs) and self-organizing maps, resolving multiple variables across various scales to produce a regional classification. In turn, the deep learning algorithms can advance efforts to define agroecoregions for the continental network of LTAR sites.

This research requires a multi-scale approach to explore both up-scaling (e.g., farm plot measurements to satellite image surface reflectance values and derived indices) and down-scaling (e.g., satellite-image derived indices of vegetation and soil properties to plot-level estimations of crop yield/health) models to address questions of regionalization and remotely sensed agricultural processes. The multi-scale study area includes three scales of nested areas at broad/regional, intermediate/watershed, and fine/farm plot landscape scales. A premise of the ability to up-scale ground-based measurements to spectral reflectance values of remotely sensed imagery is the establishment of a statistically significant correlation between: 1) a phenomenon or characteristic measured at a point or within a sample plot in an agricultural field; and 2) the surface reflectance of electromagnetic radiation recorded at that point/plot by a sensor such as a hand-held spectral radiometer or a multispectral sensor mounted on a UAS, an airplane or a satellite platform. Depending on the spatial resolution of the multispectral sensor and the height/flying height of the platform on which it is mounted, the area on the ground that is represented by a single pixel in the remotely sensed imagery will vary. The USDA-ARS Southeast Watershed Research Laboratory regularly acquires UAS imagery of crops growing in farm fields within the Little River Experimental Watershed. Seasonal UAS imagery records the growth of crops (e.g., cotton and peanuts) at 9-cm pixel resolution using a 5-band MicaSense RedEdge multispectral sensor mounted on a DJI Matrice quadcopter (M100 or M210RTK). Thus far, our primary study site is an unirrigated farm near Ashburn, GA (31°42'22" N, 83°43'30" W), during the 2018 growing season. That year the farm was split into two sets of fields: cotton and peanuts. Within the fields, the USDA-ARS laid out 42 sample points from which ground measurements (plant density, aboveground biomass, etc.) were taken. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), provided a general sense of plant health. As we explored scaling up, we look to incorporate vegetation index values in place of surface reflectance values of individual multispectral bands to provide a better assessment of plant yield. The correlation of NDVI between the 9-cm drone imagery and 30-m Landsat 8 imagery at the 42 sample points was quite low, indicating imagery of an intermediate spatial resolution, such as 3.7-m Planet or 10-m Sentinel 2A/B satellite imagery, are needed as we scale up to the regional level (table 1).

Table 1—Pearson correlation of NDVI between UAS and Landsat 8 imagery

UAS date	Landsat date	Pearson correlation
6/18	6/21	0.0516
8/3	8/2	0.0762
9/7	9/6	0.0951

NDVI = Normalized Difference Vegetation Index; UAS = unmanned aerial system.

Through our deep learning exploration to date, we created a simple binary classification model which reads an image and determines if the image captures a cotton crop or a peanut crop. Using the deep learning tools in ArcGIS Pro, we produced 626 true-color image chips (256 x 256 UAS pixels) of the farm. This was performed for a single UAS image date and samples were labeled as either cotton or peanut. We then exported these image chips to a Python environment, using the TensorFlow library to create our model. Our program read the images and built a 3-D tensor of reflectance values from 0 to 1. We chose an 80 percent training split, where 80 percent of our image chips produced the model and 20 percent validated the model's accuracy. We constructed our model by running three iterations of CNNs and max pooling, flattening the output to a 1-D array, and running a pair of fully connected neural networks. The output was a 2-D matrix which contained the probability of each image belonging to each of the class labels (i.e., cotton or peanut). We calculated the predicted class for each image by identifying the class with the highest probability. Finally, we sent our predicted classes back to ArcGIS Pro to visually inspect where any misclassified image chips were located (fig. 1). When we compiled our model, we saw that our model was nearly 100 percent accurate. This high accuracy mark indicated that our binary classification model was too simple. Moving forward,

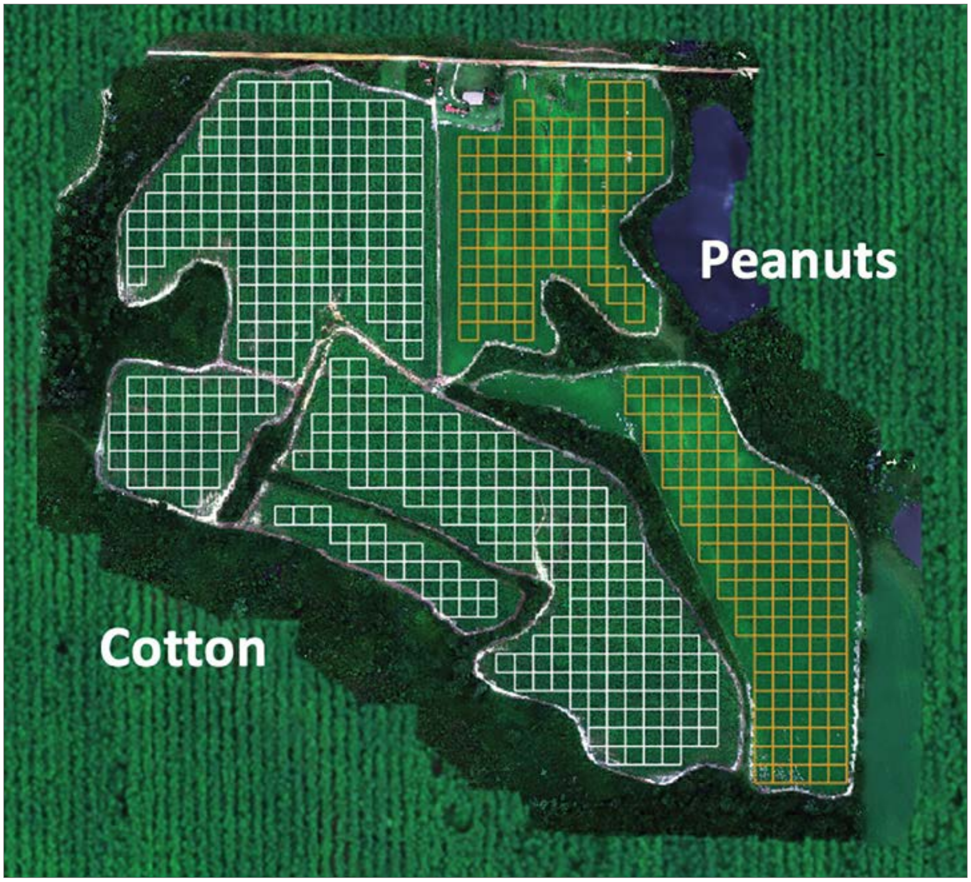

Figure 1—Deep learning image chips with borders that identify the predicted crop label (white: cotton; yellow: peanut).

we can improve our model's utility by incorporating images from additional dates and classes (other crops, water, forest, etc.), and generating smaller image chips. These improvements to the model will allow us to scale our analysis from the field level up to the regional level via multiple scales of UAS and satellite imagery.

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Expanding LTAR Capabilities with Water Parcel Tracking

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The original USDA LTAR research program proposed a standardized experimental protocol at diverse locations throughout the US, where each location would set up a paired comparison between the dominant farming practice in their region (BAU) and some aspirational farming system (ASP) designed to reduce environmental impact while maintaining or increasing profitability. For most regions, identification of the dominant farming system is relatively straightforward; in ours, the Upper Mississippi basin, that is a corn/soybean rotation, with regular tillage. However, specification at the outset of a single aspirational management system that's both more profitable and more environmentally benign is a difficult challenge; if we knew what that was, it would already be in wide use. Each location has made its best guess and the long-term comparisons have begun, but there is a need to develop methods to more broadly screen other management practices to see if there are other aspirational practices that may be superior to those that we have chosen.

Toward that end, we are developing a method to map changes in water quality as a stream moves through a watershed at the scale of a 10 or 12 digit HUC, and to relate those changes to adjoining land use, management, and conservation practices. The platform for the system is an ultralight inflatable kayak, outfitted with a GPS, depth finder, optical nitrate sensor, a multi-parameter sonde, and a datalogger that interrogates the sensors at 1 s intervals. Separately, an acoustic doppler current profiler (ADCP) is used to measure flow at discrete points along the stream. ArcGIS is used to then map streamwise changes in NO_3 load, providing a water quality map that can be used in conjunction with watershed models and GIS information on land use, topography, and management practices to assess the relative water quality impacts of those practices, both positive and negative, at a range of scales.

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The role of bioavailable phosphorus loading on Lake Erie harmful algal blooms

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The National Center for Water Quality Research has been monitoring major tributaries to Lake Erie for over 44 years as a part of its Heidelberg Tributary Loading Program (HTLP). A minimum of one sample and, during storm runoff, up to three samples a day are analyzed for all major nutrients and suspended sediments from six major tributaries to Lake Erie (Maumee, Sandusky, Portage, Huron, Raisin and Cuyahoga). Long-term trends in loads and concentrations indicate that total particulate phosphorus (TPP) has decreased since the mid-1970s in the agricultural watersheds, whereas dissolved reactive P (DRP) increased drastically in the mid-1990s corresponding to the recurrence of harmful algal blooms (HABs) in Lake Erie. Yet, HAB severity since 2002 has been equally well-described by Maumee River TPP and DRP loads as well as discharge volume from March-July, which has led to confusion on management practices to reduce bloom severity. For instance, the current target load reductions for Lake Erie include both total P (75% of which is TPP) and DRP targets. The 2019 bloom season has helped resolve some of these issues. Although 2019 March-July flow and TPP loads were among the highest ever measured, DRP loads were 30% lower than expected based on flow resulting in the 5th highest loads since 2002. DRP loads were lower than expected because exceedingly wet conditions prevented much of the typical P fertilizer and manure applications from November 2018 – June 2019. Following, bloom severity in 2019 was 7.3 on a scale of 10, or the 5th highest since monitoring via satellites began in 2002. In comparison, the highest bloom severity measured was in 2015 (10.5), which had the highest March – July flow and DRP load. Yet, because most of the storm events occurred in June and July when crops were already growing, TPP loads were 30% lower than expected. These comparisons highlight the strong influence of DRP on bloom severity and the comparatively minimal influence of TPP. Management to reduce bloom intensity in Lake Erie should prioritize practices that reduce DRP losses over those that focus on erosion control.

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Section 16: Poster Session

USDA-ARS, Watkinsville, GA, 1937–2012: legacy of 75 years of watershed research

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Established in 1937 as 1 of 15 regional Federal Soil Conservation Service experiment stations, the Center was transferred to the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) in 1953. The 478-ha Center went through several name changes from the Southern Piedmont Experiment Station in 1937 to the J. Phil Campbell, Sr., Natural Resource Conservation Center in 1998. Research addressed impacts of historic soil erosion and mitigation technologies in the Piedmont. Pioneering work was conducted in soils, hydrology, conservation tillage, cropping systems, cover crops, rotations, forage and pasture management, and integrated soil and water management systems, advancing the conservation movement in the Southeast United States and elsewhere. Benefits such as increases in soil carbon, physical condition, and infiltration, N use efficiency, farm level economic stability, and yield were demonstrated. Seminal work on pesticide transport in runoff from conventional tillage fields was conducted in collaboration with the U.S. Environmental Protection Agency (USEPA). Soil sequestration of atmospheric CO_2 through conversion of degraded croplands to pastures with heavy residue conservation tillage systems was established. Risks of broiler litter use as fertilizer were identified but reduced with good management practices. Legacy data were used to predict management effects on soil and water losses and to define regularity of agricultural and hydrologic droughts. Historic data were used to show that Universal Soil Loss Equation (USLE) hydrologic curve numbers in published tables were 10+ units greater than required for well-established, no-till fields. Flue gas desulfurization gypsum was safe and effective for reducing runoff P losses from broiler litter amended pastures. Research conducted at the site related agricultural land use and management to spatial and temporal distribution of nutrients, sediment, and fecal coliforms in two large watersheds. This research was recognized as a prototype for evaluating agricultural TMDLs. Small ponds within agricultural landscapes were shown to reduce populations of fecal microorganisms in outflow. This indicated that strategic landscape placement of ponds is an effective management option for reducing off-site

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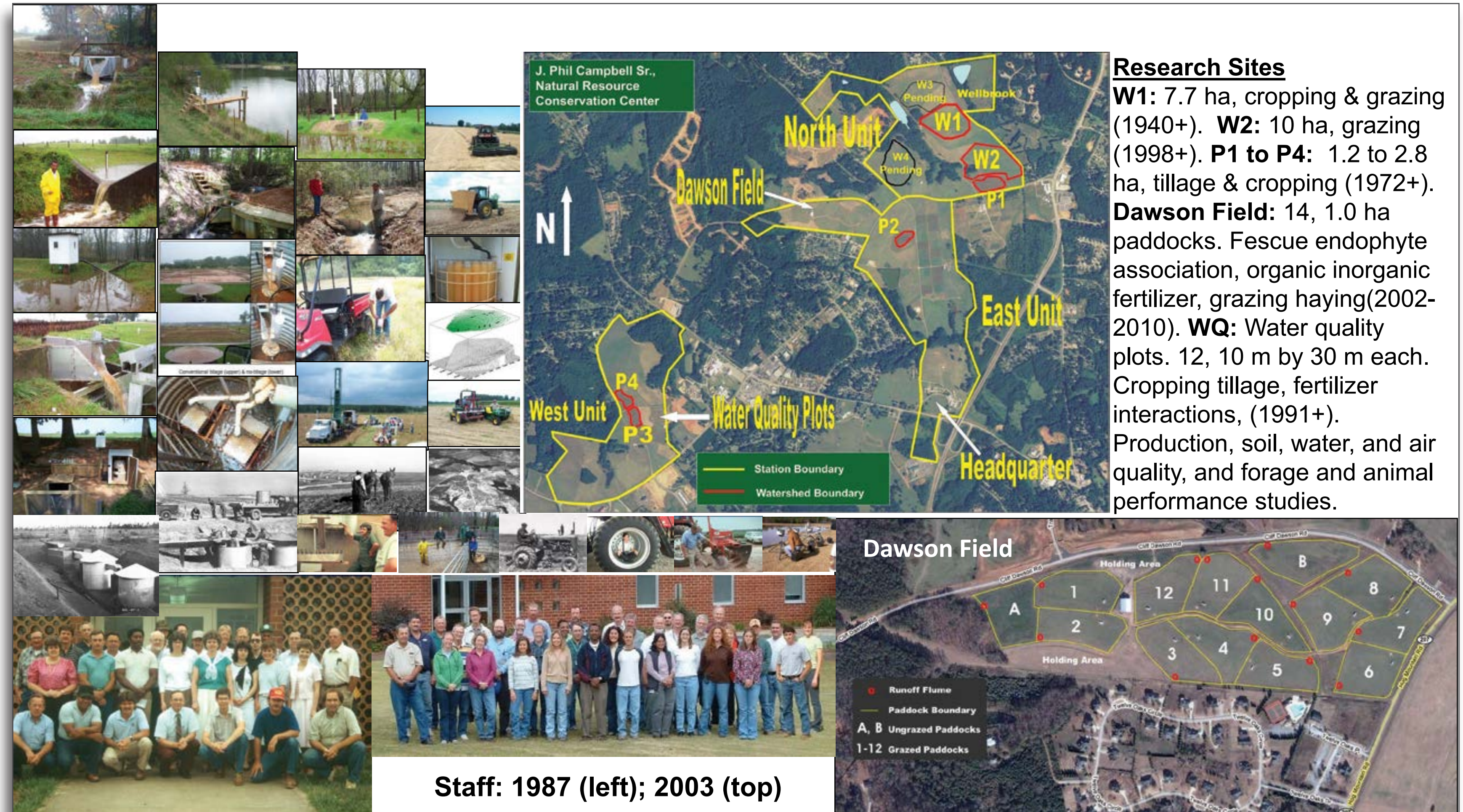

Figure 1—Layout, hydrologic monitoring infrastructure, and staff at the ARS Research Center, Watkinsville GA.

movement of microorganisms that impair water quality. The Center's long-term research plots, fields, and watersheds served as an outdoor laboratory and technology transfer site providing information to U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS), USEPA, grower and commodity groups, university students, and other national and international researchers. The research contributed to development and testing of erosion, water quality, and hydrologic models, including USLE, Revised Universal Soil Loss Equation (RUSLE), RUSLE2, Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS), Water Erosion Prediction Project (WEPP), Wind Erosion Prediction System (WEPS), and Root Zone Water Quality Model (RZWQM). The USDA transferred the research center to the University of Georgia (UGA) in 2012. The legacy continues of landscape-scale research critical for understanding impacts of land management in the Southern Piedmont.

Table 1— Status of watershed research sites as of 2011, USDA-ARS, Watkinsville GA

Name	Year	Size, description	Original purpose	Previous studies	Current studies	Current features	Data availability
ON-STATION							
W1	1939	7.7 ha, 3-10% slope	Runoff and erosion from row cropping, cover crops	Row crops (5-yr), kudzu (5-yr), grazed kudzu & rescue grass (7-yr), grazed bermudagrass & winter annuals since 1960	Water quality impacts of grazing & calving management	V-notch weir with pressure transducer, recording rain gauge, automated water sampler (1999+), 5 piezometers, 1 monitoring well (2000+): 1.2m soil moisture TDR probes 1998-2001 at 12 sites	USDA Hydrology Lab. (HL) 1945-84.
P1	1972	2.5 ha, 2-10% slope	P1-P4: Pesticide losses in runoff from row crops under convention tillage	No-till, double cropped since 1975.	P1-P4: 1998-2005 No-till with & without paraplowing: hydrology, water quality & crop productivity. 2006+ integrating stocker cattle in no-till cotton production. Water quantity and quality (including effect of poultry litter fertilizer), soil quality (spatial variability), crop productivity. P, N, sediment, and bacterial losses.	2.5′ H flumes. Automated rain gauges, water samplers, and stage height recorders installed in 1998. Paper recording devices used previously.	HL: 1972-73. All data digitized.
P2	1972	1.3 ha, 2-5% slope		Management includes 6-yr bermudagrass & 2-yr grazed millet.			HL:1973-75 Runoff digitized 1984-98.
P3	1972	1.4 ha, 3% slope		P3-P4: 1993-1999 contrast of cotton with crimson clover vs. rye cover crops			HL:1972-75 Runoff digitized 1982-98
P4	1972	1.2 ha, 3% slope					HL:1973-75 Runoff digitized 1984-98

(continued)

Table 1 (continued)— Status of watershed research sites as of 2011, USDA-ARS, Watkinsville GA

Name	Year	Size, description	Original purpose	Previous studies	Current studies	Current features	Data availability
Water Quality Plots	1992	12 plots, 10 x 30 m, slope < 1%	Cover crop effect on nitrate leaching.	Tillage and poultry litter effects on N, P, herbicide, bacterial, and hormone losses from cotton-rye and corn-rye studies. Rainfall simulation study measuring fate of nutrients.	Millet production in conventional tillage and no-tillage.	Each plot has a flume with shaft encoder and Coshocton wheel, tile drains with tipping buckets, automated water samplers, soil moisture content, micro-meteorological data. Storm surge caused data loss	1992-2000: drainage, crop yield, soil data; 2001 - 2003: drainage, runoff, crop yield, soil data; 2004 – 2010: crop yield & soil data
W2	1999	10 ha paddock	Surface and sub-surface hydrology; transport of crypto-sporidium and bacteria to springs from pasture	One of many rotational grazing pastures with limited monitoring	Surface and sub-surface hydrology, transport of nutrients to springs from pasture; wetland effects on nutrients.	Instrumented spring with 1-ft H-flume and automated sampler. 6" H-flume for baseflow of stream and 4.5' runoff flume and automated sampler. Grid of piezometers, monitoring wells, tensiometers, observation wells.	Monthly summary of hydrology and nutrient data
North Unit Water-shed	1998	~100 ha	Hydrologic processes, model validation for a "typical" S. Piedmont head-waters stream.	One cropped catchment since 1972 (P1). Rest part of rotational grazing pastures.	Effect of impoundments on water quality in a headwater stream: bacteria and nutrients.	Mixed land use (grazing, forested, cropped), 3 research catchments (W1, W2, and P1), stream sampling at spring, above and below a pond.	Monthly baseflow samples for nutrients and pathogens, hydrology data.
Dawson Field	2002	14 pad-docks each of 1.0 ha size: 12 grazed and 2 hayed	Impact of fescue endophyte infection & poultry litter on forage & animal production, soil quality, & hydrology.	Characterization of landscape and texture; small scale spatial variability of soil quality;	Continuing original purpose	Paddocks hydrologically separated, each with 1.5-ft H-flume and composite sampler for runoff. In-house built composite sample collection.	Rainfall, runoff, & nutrient data: 2002-2008. Soil C sequestration and total N; Fescue growth and cattle performance

(continued)

Table 1 (continued)— Status of watershed research sites as of 2011, USDA-ARS, Watkinsville GA

Name	Year	Size, descrip-tion	Original purpose	Previous studies	Current studies	Current features	Data availability
OFF-STATION							
Rose and Green-briar Creeks	1997	~90 km^2 each	Land management impacts on water quality. Spatial & temporal distributions of N, P, & sediment in watersheds. Evaluate quality of test kits & volunteer water quality monitoring	None	Bacterial sampling being added.	Distributed on-farm sampling at edge of field, upstream & downstream. Participatory research and outreach. Includes natural features such as beaver dams, Oconee National Forest, and Lake Oconee	1999-2005: Monthly baseflow data
Upper Oconee River Basin HUC: 3070101	1998	7576 km^2	Develop monitoring strategies & accountability for conserva-tion practices and programs	Monitored sub-watersheds of EQIP priority areas three years (1999-2002). Includes regions with concentrated poultry production with litter applied to pastures; dairy, mixed agricultural land use; and city of Athens and a major hydroelectric, recreational, and residential lake.	Externally funded research completed.	None	1999-2002: bi-weekly nutrient and bacteria data from 25 sites

Note: the USDA transferred the research center to the University of Georgia in 2012.

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Advancing Understanding of Total and Reactive Phosphorus Concentration and Suspended Solids Particle Size Class

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The correlation of soil to nutrient losses from upland areas to receiving water bodies continues to be an important, yet often confounding, source of error in watershed planning. In particular, loadings of suspended solids and phosphorus (Total P and soluble reactive SRP) have been reported in many studies. However, the relationships between P and SRP and specific soil particle size classes remain largely unknown. This study was initiated to develop an empirical relationship between P, SRP and suspended solid concentrations and particle size (mg/L and µm, respectively) in a representative Appalachian mixed-land-use watershed. Event-based water samples (n = 128) were collected from agricultural, urban and forested reaches in West Run Watershed, located in Morgantown, WV, USA. Preliminary analyses show average P and SRP concentrations of 0.4 and 0.31 mg/L for P and SRP, respectively, while minimum and maximum concentrations ranged from 0.0 - 5.03 mg/L (P) and 0.0 - 4.56 mg/L (SRP). Average, minimum, maximum and standard deviation (SD) values of turbidity were 27.82, 0.46, 621 and 74.35 NTU, respectively. Mean, minimum, maximum and SD values of total suspended solids (TSS) were 25.3, 0.0, 402.0, 26.6 mg/L respectively. On average, 93%, 33%, and 0.0% of particle size classes for all samples were below or equal to 62.23 µm, 5.5 µm and 0.072 µm, respectively. Preliminary analyses further indicate that highest P and SRP concentrations corresponded to particle size classes below 62.23 µm and above 0.072 µm. Ongoing analyses will include elucidation of which particle size classes corresponded most significantly ($\alpha = 0.05$) with P and SRP. This work is important given that phosphorus has been identified as a principal driver of degraded aquatic health in fresh water. Results of this investigation will provide quantitative information that will advance the ability of land managers and policy makers to target specific practices that may reduce particle size class transport and remediate the fate of total and reactive phosphorus.

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Improved site-specific allometric equations for *Robinia pseudoacacia*

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Robinia pseudoacacia is an early successional nitrogen (N)-fixing tree, native to the Southeastern U.S. It is widespread in the southern Appalachians, particularly following disturbance, and can be a significant source of new N to recovering forests. Average N-fixation rates range from 2–9 kg N ha^{-1} $year^{-1}$, depending on stand age and density of *Robinia* stems. *Robinia* is a functionally important tree species, not only because it fixes N and increases soil N availability, but also because it has more conservative daily water use than other common early successional trees, such as *Liriodendron tulipifera*. Because *Robinia* plays an important role in southern Appalachian forest dynamics and ecosystem processes, models are needed to accurately predict its aboveground biomass and sapwood area.

We developed allometric equations for *Robinia pseudoacacia* to predict aboveground biomass (leaf, wood) and sapwood area based on measurements of diameter and height. We compiled data across three research studies, 16 trees, ranging in diameter from 6.0 to 58.5 cm diameter at breast height (dbh). All trees were destructively harvested, dry biomass of leaves and stems measured, and C and N concentration of all tissues were estimated. We present these equations to provide improved site-specific forest biomass estimates.

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Characteristics of flow events that influence phosphorus and nitrogen loads from ranchlands of South-central Florida

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South central Florida faces major challenges in protecting water quality and wetland ecosystems in the face of encroaching development and significant agricultural production. Beef cattle ranches are the largest land use in the Lake Okeechobee watershed, and although nutrient loads from cattle pastures are low relative to other land uses on a per area basis, the large acreage of ranches makes them a significant contributor to overall nutrient loads. Even though best management practices and other management techniques have been implemented to improve nutrient run-off from ranches, high variability between flow events still occurs suggesting that there are other factors that may be affecting nutrient discharges from ranchlands. The objective of this study was to use a model selection approach combined with multivariate regression analyses to reveal the main factors affecting ranchland nutrient loads using data collected during the Florida Ranchlands Environmental Services Project. In general, across three ranches and eight catchments, large flow events discharged greater nutrient loads; for both P and N the top five flow events accounted for one third of the P discharges and one quarter of the N discharges over the three year study (n=62). Differences between sites contributed to variation in nutrient loads for both unit area loads and flow-weighted loads. However, even though site variation had a strong effect in all models, we still detected strong effects of other factors. Peak flow intensity consistently was retained in regression models and had the highest effect size in relation to other variables on unit area P and N loads. This supports implementation of management techniques to slow down flow rates to aid in reducing both P and N release. Adaptively managing for large flow events by creating more storage space (e.g. Releasing water and raising board heights) before anticipated large storm events may also help to reduce total P discharges from ranchlands.

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Application of Remote Sensing Drought Indicators for Monitoring Drought and Streamflow

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This project analyzes the in-situ drought indices the Palmer Drought Severity Index (PDSI) and the Standardize Precipitation Index (SPI) and the remote sensing drought indices, the Vegetation Condition Index (VCI) and the Soil Moisture Condition Index (SMCI) in predicting streamflow anomalies. data for the growing season (April-September) from 2003 through 2017. Growing season data from 2003-2017 were compared on a climate division basis for climate divisions in the four states of Kansas, Missouri, Nebraska, and Iowa. Results show that SMCI is significantly correlated with PDSI and SPI more than VCI in the region. The Percentage of Discharge Anomalies (PDA) were used to compare streamflow discharge with each index over the time frame for each climate division. PDA tended to match closest to SPI and PDSI. VCI and SMCI changes followed a more annual cycle. Results suggest that PDSI and SPI can reasonably (statistically significant) predict streamflow changes in most climate divisions. VCI showed significant correlations in the western parts of the study region while SMCI showed higher significance overall in monitoring PDA over the study region.

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Incorporating Human Dimensions in Long-Term Agroecosystem Research Network

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The USDA Long-Term Agroecosystem Research (LTAR) network, established in 2014, consists of eighteen sites located across the US. Currently, most agricultural science in the U.S. focuses on improving productivity and efficiency. The LTAR network is unique in that the experimental, multi-scalar, and long-term research also addresses sustainable intensification of agroecosystem productivity, climate change, environmental conservation, and promotion of prosperity. The incorporation of a Human Dimensions working group will be instrumental in achieving the overarching goals of the LTAR network by including social, economic, cultural, and other human community-based components of long-term agroecosystem research.

The overall goal of this research is to engage stakeholders in the contribution of human dimensions components to evaluating business as usual (BAU) systems and envisioning aspirational (ASP) systems. The research will develop methods and indicators to assess impacts to rural prosperity and human well-being; identify opportunities and barriers to the adoption of sustainable agroecosystem management strategies; and develop and deliver knowledge, tools, and products to facilitate the adoption of aspirational agricultural production strategies and innovations. In the initial phase, the objectives are to review the relevant literature and existing indicator frameworks. Preliminary findings identifying secondary data for use as indicators in the LTAR network will also described. Methodological scenarios for identifying representative BAU and ASP systems will be identified in cooperation with other LTAR working groups to help address the uncertainty and complexities decision-makers face.

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Water Footprint of Agricultural Crops: A Meta-analysis on Current Understanding and Future Perspectives

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Agriculture, the most water intense production system, which is the backbone of the economy for many countries, extracts two-third of water from lakes, rivers, and aquifers. Agricultural crop water requirements vary between crops. The Water Footprint (WFP) is a measure of freshwater consumption in food production and its impacts on water resources by individuals, communities, and businesses. It is partitioned into green WFP that denotes rainwater use and blue WFP, ground, and surface water. The present study focuses on the current understanding of the WFP concept, different phases, methodologies adopted, and the accounting from peer-reviewed literature from a qualitative perspective. A meta-analysis was done from published articles related to the agricultural WFP of crops from the google scholar database for 2006 to 2020. The results show that majority of the studies have focused on the WFP accounting phase, with a focus on the sustainability assessment phase in recent years. The progress of WFP research shows an increase in studies related to impact assessment, specifically for blue water. Therefore, future studies should consider green water impact assessment also in the analysis. Besides, WFP assessments may be done within the framework of water-food-energy nexus for a complete understanding of water resource and environmental management decisions.

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Evapotranspiration in a subtropical wetland savanna using low-cost lysimeter, eddy covariance, and modeling approaches

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Evapotranspiration (ET) constitutes the largest loss of water from subtropical and tropical grassland and wetland ecosystems, yet ET data are beset with high uncertainty at the landscape scale as there is not much information on plant water use in these ecosystems. The major reason for the paucity of data in much of the world is the complexity and expense of ground-based methods for measuring ET such as lysimeters and eddy covariance systems. The ensuing uncertainty in ET estimates in turn affects water resources management, drought forecasting, and assessing the vulnerability of ecosystems to climate variability and land use change. A recent assessment across the U.S. Long-Term Agroecological Research Network (Baffaut and others 2020) found considerable uncertainty in ET estimates stemming from the wide variety of methods used to estimate ET and identified ET as a key area needing further refinement in measurement.

This study developed two different low-cost lysimeters (under US$50)—a weighing-type and a water level difference lysimeter—to measure daily ET under controlled watering conditions over 2018 for single species as well as grassland and wetland plant communities. The study site was Buck Island Ranch (Archbold Biological Station) located in the headwaters of the Everglades in southcentral Florida, where the dominant land use is cattle ranching occurring across a mosaic of grassland, wetlands, and oak-palm woodlands.

The weighing-type lysimeter consisted of a single plant species growing in a pot that was watered to field capacity, weighed (Mettler-Toledo 0.1g precision) and then weighed again after 2 to 3 days. The difference in weight was attributed to ET over that time period because outflow and biomass gain were negligible and rainfall was excluded by location of the lysimeter in an open-sided

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shade house with transparent plastic roof (~90 percent transmittance). Common grassland and wetland species were chosen for these lysimeters to see if there were any detectable differences in ET between species—the grasses *Axonopus fissifolius* and *Paspalum notatum*, the forb *Phyla nodiflora*, and the sedge *Rhynchospora colorata*.

The water level lysimeter consisted of three to four pots of plants placed in a mesocosm (80-cm diameter, 40–55 cm high) with water filled up to a certain level, also placed in an open-sided shade house. The drop in water level after a week was noted, and this volume was attributed to open water evaporation and potential ET (soil evaporation + plant transpiration). Some lysimeters served as controls with pots covered with aluminum foil to prevent ET and thereby provided open water evaporation values. Plants used were graminoid species or mixed plant communities comprised of grasses, sedges, rushes, and forbs.

Lysimeter ET values were then compared with ET values from an eddy covariance tower onsite (latent heat method), as well as with commonly used vapor transport-based ET models for the region: FAO Penman-Monteith (Allen and others 1998), Modified Turc (Turc 1961), Abtew Simple Radiation Model (Abtew 1996) and ET data from the Florida Automated Weather Network (https://fawn.ifas.ufl.edu/).

Both weighing-type and water level lysimeters showed the expected increase in ET over the growing summer season (fig. 1) that was also shown by ET models and eddy covariance ET. Furthermore, an uncharacteristic ET dip in May owing to extreme cloudiness was shown by both lysimeter types as well as the eddy flux and ET model estimates. Annual ET measurements from weighing lysimeters (881–1278 mm; n = 20) and water level lysimeters (average 1085 mm; n = 30) were

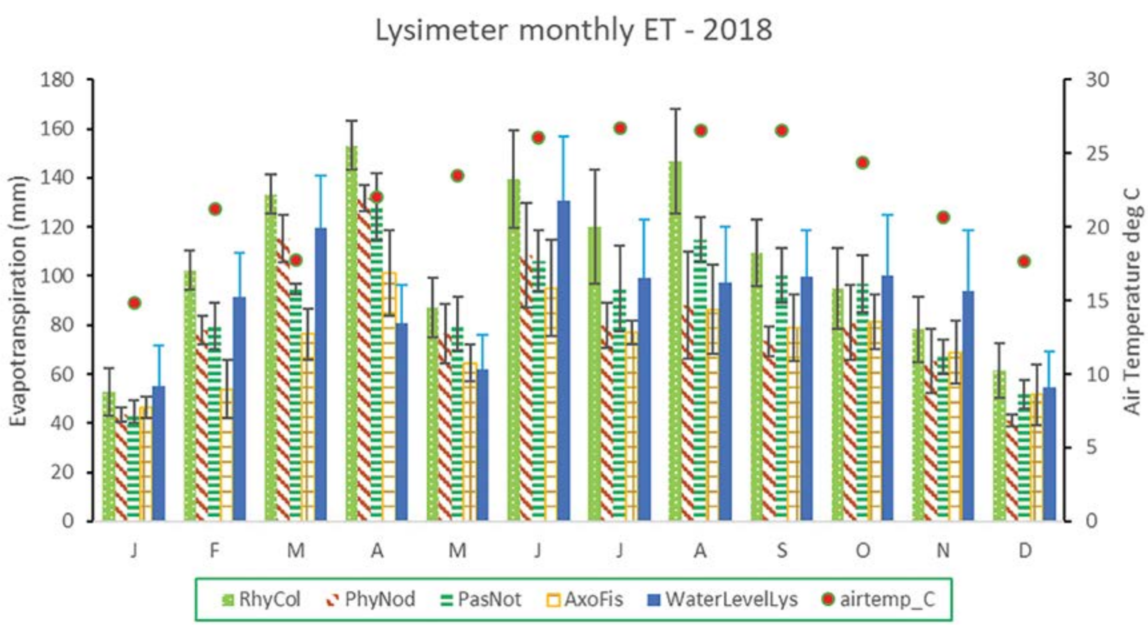

Figure 1—Monthly evapotranspiration for weighing lysimeters (n=5 per species, 6-letter codes indicate species) and water level lysimeters (n=30). Error bars indicate one standard deviation. *Rhynchospora colorata* (RhyCol) has the highest monthly ET, *Phyla nodiflora* (PhyNod) and *Paspalum notatum* (PasNot) have intermediate ET, while *Axonopus fissifolius* (AxoFis) has the lowest ET. Monthly average air temperature is shown by red dots.

similar to model estimates (1000–1200 mm). Eddy covariance ET estimates were lower (722 mm, but missing data for February and March) and similar to lysimeter measurements for *P. notatum* (855 mm for 10 months), the dominant grass in the flux tower footprint. Lysimeters were also found to be sensitive to species level ET differences, likely caused by differential water uptake patterns, with the sedge *R. colorata* having the consistently highest ET over the year, and *A. fissifolius* with the lowest ET.

There are some considerations to be borne in mind while interpreting data from these lysimeters. The ET values obtained are between potential ET and actual field ET because the lysimeters are excluded from rainfall but periodically watered (intermittent saturation and drying out), and the pots confine the roots. Despite these limitations, the simplicity and performance of these low-cost lysimeters suggest potential for use as independent field data sources to calibrate regional ET models or datasets such as MODIS-16 (Mu and others 2007), particularly for data-poor regions of the world.

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(continued)

Table 1—Annual evapotranspiration from lysimeters, eddy covariance, and models for 2018 at Buck Island Ranch, south Florida

Evapotranspiration Method	Annual ET (mm)	ET spatial scope
Eddy_Covariance (10 month)	722[a]	Flux Tower footprint: improved pasture
Weighing Type Lysimeter PasNot (10 month)	855[a]	
Weighing Type Lysimeter_ AxoFis	881	Single species in a pot (n=5 lysimeters)
Weighing Type Lysimeter _PhyNod	982	Single species in a pot (n=5 lysimeters)
Weighing Type Lysimeter _PasNot	1060	Single species in a pot (n=5 lysimeters)
Weighing Type Lysimeter _RhyCol	1278	Single species in a pot (n=5 lysimeters)
Water Level Lysimeter Mixed_communities	1085	Plant communities in pots (n=30 lysimeters)
FAWN data for Okeechobee	1061	Regional ET at Okeechobee,FL
Modified Turc model	1317	Regional PET
Abtew_net radiation model	1366	Regional PET
FAO_Penman-Monteith	1370	Regional PET

[a] Eddy covariance annual ET is missing data for February and March. Hence weighing lysimeter data for PasNot omitting February and March is also shown for comparison purposes.

Note: the annual rainfall at Buck Island Ranch for 2018 was 1170 mm.

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Impacts of pasture, hay, and row crop management systems on groundwater quality and quantity in the Santa Fe River basin, Florida

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The Upper Floridan Aquifer, which is underlies all of north Florida, is threatened by over-pumping and nutrient enrichment. In the Santa River Basin, north Florida, agriculture has been identified as a large groundwater user and a primary source of nutrients in groundwater and the springs and rivers it feeds. Grazed pasture, hay and row crops are the major agricultural land uses in the Santa Fe basin, occupying approximately 12%, 4% and 5% of the basin area respectively. The main objectives of this study were to quantify the water and nutrient footprints for grazed pasture, hay and row crops in the Santa Fe Basin using the Soil and Water Assessment Tool (SWAT). SWAT was calibrated and validated using available experimental data for corn-peanut rotations (Zamora et al, 2018) and Bermuda grass (Graetz et al 2006; Overman et al, 1991), then used to evaluate yield, net groundwater recharge, and nitrate leaching over a range of management systems commonly used for each of these land uses. Results showed that for corn-peanut rotations different management systems produced approximately equivalent yields, but large variations groundwater recharge and nitrate leaching. For pastures different management systems produced approximately equivalent yields and groundwater recharge, but large variations in nitrate leaching. Hay management systems showed large variation in yields, but small variation in groundwater recharge and nitrate leaching. Results of this study should be useful for incentivizing growers to adopt management practices with lower water and nutrient footprints, and for estimating the land use and land management changes required to achieve aquifer, spring and river protection in the Santa Fe Basin.

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These proceedings contain the full-length papers, extended abstracts, and short-form abstracts of oral presentations and posters given at the Seventh Interagency Conference on Research in the Watersheds (7th ICRW)—Enhancing Landscapes for Sustainable Intensification and Watershed Resiliency, jointly hosted by the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) and the University of Georgia, Tifton, GA, and held virtually November 16–19, 2020.

The 7th ICRW focused on the science and management of increased human and natural drivers of watershed change throughout the United States. The conference was structured to present and address key scientific and management issues faced by watershed managers and scientists throughout the U.S. Research was presented by Federal, State, and local scientists, academics, and non-governmental organizations focusing on managing complex watershed systems and watershed components (e.g., streams, rivers, lakes, estuaries, etc.). Thematic areas included watershed modeling, responses to climate change, management strategies, integration of science and management, water quality and quantity, long-term agroecosystem science, as well as ecosystem-specific themes such as coastal plain watersheds and wetlands.

The conference was hosted by the USDA-ARS and the University of Georgia, with material and in-kind support from the following organizations: Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), the USDA Forest Service, the U.S. Geological Survey, the U.S. Bureau of Land Management, the U.S. Fish and Wildlife Service, the U.S. Environmental Protection Agency, NASA, and the U.S. Department of Energy.

The 7th ICRW was built on the foundation laid by the previous hosting organizations: USDA Agricultural Research Service (2003), USDA Forest Service (2006 and 2015), U.S. Geological Survey and CUAHSI (2009), the Bureau of Land Management and National Park Service (2011), and U.S. Environmental Protection Agency (2018). The 8th ICRW will be hosted by the U.S. Geological Survey in Corvallis, Oregon. The conference is planned for June 2023.

Keywords: watershed modeling and conservation, coastal habitats, coastal watersheds, extreme climatic events, evapotranspiration, hydrologic modeling, land use, monitoring, stream and river networks, transboundary waters, watershed management, watershed science.

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