Collaborative Research to Prioritize and Model the Runoff Volume Sensitivities of Tidal Headwaters

A Final Report Submitted to the

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Abstract

Non-point source pollution from stormwater runoff associated with large-scale land use changes threatens the integrity of ecologically and economically valuable estuarine ecosystems. Beaufort County, SC implemented volume-based stormwater regulations on the rationale that if volume discharge is controlled, contaminant loading will also be controlled. The County seeks to identify which of their tidal creeks and what portions of the creeks are most sensitive to stormwater runoff.

Through an ongoing collaborative process with county staff and officials as well concerned citizens, four watersheds, with a fifth added for validation, of critical interest were instrumented with rain gauges and salinity sensor arrays to monitor the movement of freshwater down these systems from volume "sensitive" headwaters to volume "insensitive" downstream waters. A total of 32 sites were monitored with 791 salinity responses to rain events captured. The change in salinity was measured as the primary indicator of the volume of stormwater entering the estuarine ecosystem. Salinity was filtered using a 13.5 and 25 hour moving average to remove the tidal fluctuations observed in estuarine systems in South Carolina, thereby allowing us to isolate the stormwater impacts from tidal effects. Statistical analyses were conducted on the salinity data, rainfall, and various watershed parameters to develop predictive models. A watersheds study was conducted across all Beaufort County major watersheds to scale up the findings of this study. Stormwater runoff was also modeled with the Stormwater Runoff Modeling System (SWARM) to estimate the expected runoff based on watershed area, land cover, soils, and slope. SWARM was used to project impacts of climate change and engineered stormwater retrofits on tidal creeks.

Four major outcomes resulted from this project. First, a strong working relationship has been forged with the range of relevant Intended Users including the establishment of a Watershed Advisory Committee that has helped drive data collection, analysis, synthesis, and translation. Second, correlations between rainfall amount and salinity drop were developed in order to define volume sensitive areas, and locations within each system have been designated as more volume sensitive. Third, a ranking of all Beaufort County watersheds as either more or less volume sensitive has been made based on a range of different analyses. Fourth, best management practices (BMP) and climate change scenarios were developed for the six volume sensitive watersheds; the scenarios will enhance understanding of impacts of future conditions in Beaufort County. This information will permit Beaufort County to focus policy and stormwater management actions on the portions within a tidal creek as well as which creeks are more sensitive to stormwater inputs.

Management Problem and Context

Non-point source pollution from stormwater runoff associated with rapid coastal human population growth and large-scale land use changes threaten the integrity of ecologically and economically valuable estuarine ecosystems worldwide. Climate change is expected to exacerbate these stormwater problems (Karl et al. 2009). A portion of the ACE Basin lies within Beaufort County, South Carolina, a community very concerned about the threat of stormwater degrading its estuarine environments, a challenge that figures prominently in its Comprehensive

Plan, local media, and government affairs (Van Dolah et al. 2000, Island Packet 2001, Beaufort County 2007, Pollack and Walker Szivak 2007, Town of Bluffton 2008). This concern is also cited as a priority for the ACE Basin NERR in its 2011-2016 Management Plan and its Coastal Training Program (CTP) Strategic Plan (Maier 2010, Walker 2010). The Reserve has been actively involved with Beaufort County in addressing stormwater issues through its CTP and Stewardship activities. Beaufort County's rapid growth (83% between 1990 and 2006 and an additional 70% increase expected through 2025) makes it particularly susceptible to environmental degradation from stormwater runoff (Beaufort County 2007). The local population is particularly concerned that, in addition to runoff transporting biological and chemical contaminants, the "flashiness" of salinity changes due to stormwater influx of freshwater may negatively affect larval recruitment and survival of shellfish, crustaceans, and fish in the marshes. The health of these fishery resources is of the highest priority for local residents and rapid salinity changes are considered locally to be as much a problem as contaminants or nutrient enrichment (Barber 2008, Town of Bluffton 2008).

The County has modified its stormwater requirements to include water quantity control (runoff volume) within their Best Management Practices (BMP) manual in addition to water quality (Ahern et al. 2012). The County's rationale is that reducing the runoff of stormwater into estuaries results in fewer bacterial, nutrient, and chemical contaminants as well as less rapid salinity changes (J.R. McFee, County Engineering and Infrastructure Director, personal communication). Beaufort County has implemented some of the toughest regulations in the country, which may serve as a model for coastal communities nationally. Within specifically identified "volume sensitive" watersheds they may require that all stormwater be retained on site through a variety of Low Impact Development (LID) approaches.

Three barriers have been identified by the Intended User group which invited us to partner with them. First, a significant barrier to implementing Beaufort County's volume control plan is the lack of scientific data necessary to identify those watersheds and portions of creeks which are more sensitive to stormwater runoff. Beaufort County's stormwater standards have been contentious at times considering the financial impact to developers and property owners. Secondly, the Beaufort County recognized that it lacked the internal capacity to conduct the necessary studies. Early in 2012, the County approached the South Carolina Department of Natural Resources (SCDNR), the ACE Basin NERR, and the University of South Carolina at Beaufort (USCB) with a request to help it identify specific volume sensitive waters, based upon scientifically rigorous data, so that appropriate regulations could be applied to those areas. A five-year cooperative Memorandum of Understanding (MOU) between Beaufort County, SCDNR, USCB, and the Town of Bluffton was developed and approved by County Council with a commitment of funds to begin the process of both identifying these watersheds and assessing whether the observed salinity fluctuations (flashiness) in tidal creeks negatively affect key fishery resources. The level at which these funds were allocated represented a third significant barrier, in that it would take at least five years to obtain the desired data. This constraint on funding meant that only one or two creek systems per year could be assessed with minimal data collection. It would also mean that these critical, user-prioritized watersheds would be monitored in different years, making volume sensitivity assessments challenging. This collaborative project provides Beaufort County with the data they need in order to address policy in a timely manner.

The data will be available for incorporation into their next Stormwater Management Plan (2016-2026).

The immediate Intended Users impacted by this problem are the Beaufort County Council elected officials, the Council-appointed Stormwater Management Utility Board (SWMUB) who represent each legal jurisdiction of the County including Town of Bluffton, and the Beaufort County Stormwater Management Division professional staff, all of whom are charged with managing stormwater within Beaufort County. In addition, we established and worked throughout the project with a Watershed Advisory Committee (WAC). The WAC was comprised of SWMUB members, Beaufort County stormwater staff, and various others involved in water quality or natural resource conservation in Beaufort County. All of these entities are insistent on strong scientific justification for any major changes to stormwater policies. Coastal municipalities throughout South Carolina and the Southeast are all faced with similar challenges and are watching Beaufort County's experience with implementing strict volume control ordinances.

The barriers listed above were used to formulate, along with input from the Intended User Group, the following project questions answered by this project:

1. *Can the major watersheds in the County be prioritized based on the extent and severity of volume sensitive waters?* Working in partnership with the WAC, SCDNR and USCB monitored rainfall and salinity responses in the drainages of five watersheds of critical interest to Beaufort County. The resulting profiles have helped define how these waters respond seasonally and tidally to rain events and the extent of the impact downstream until it is attenuated. These profiles will permit Beaufort County to rank its watersheds in terms of volume sensitive areas and to focus policy and regulatory decisions on those locations that are most critical. The concurrent acquisition of data across several watersheds during the study period addresses the three barriers cited above.

2. *How will these critical volume sensitive waters respond to implementation of volume control BMPs and to possible climate change scenarios?* A partnering scientist at the National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science (NOAA-NCCOS) Hollings Marine Laboratory (HML) has incorporated the rainfall and relevant landscape data into a stormwater runoff model called SWARM for projecting expected changes in stormwater runoff due to changing BMPs and precipitation patterns (Blair et al. 2014a, 2014b). This model has been developed specifically for the soils and topography found in coastal South Carolina. The results provide Beaufort County officials and professional staff with projections of the effect the implementation of different stormwater management policies will have on the identified volume sensitive watersheds. The model also evaluates the impacts on these watersheds of altered precipitation patterns projected by various climate change scenarios. While not necessarily required to address the three identified barriers, this component is welcomed by the Intended Users as a tool to help them evaluate possible engineered retrofits for priority watersheds. This management community has indicated an interest in designing stormwater management policies that are robust to possible future climate alterations.

The specific collaborative objectives, as defined in the proposal, were to:

1. Ensure that the publically appointed members of the Stormwater Management Utility Board thoroughly understand the research they have previously endorsed, are well informed as the project progresses, and are likely to embrace the results of the studies.
2. Engage the engineers and professional staff of the County and SWMUB for advice and assistance in additional watershed selection, specific site locations, interpretation of results, site-specific modeling modifications, synthesis of results, and translation of results for the Intended User community charged with policy development.
3. Enable community groups that routinely work with elected officials and professional staff on local environmental issues to understand and disseminate the results and analyses generated by this project.

The applied science objectives, as defined in the proposal, were to:

1. Assess the relationship between rainfall and salinity range throughout the length of tidal creeks in Beaufort County-selected watersheds in order to define what size water bodies and which particular watersheds are most volume sensitive.
2. Project the potential impacts that implementation of volume control BMPs and changing precipitation patterns might have on salinity range in priority watersheds.

Outcomes, Methods and Data

Outcomes

This study has been successful in achieving our objectives, although we have modified them in some cases based on the collaborative process. For example, the SWMUB representatives worked with us to develop a Watershed Advisory Committee (WAC) to ensure that we worked directly with all three stakeholder groups in one venue instead of engaging the groups separately as identified in our original proposal. In addition, we have also achieved additional outcomes based on questions raised by the WAC as new data were collected. For example, we did not originally plan to continue monitoring beyond a one year time period; however, the WAC suggested we try to obtain additional larger size events. The following text provides a summary of our major outcomes followed by the methods, data, and an overall project summary of the findings.

The first major outcome for the project was the establishment of a strong working relationship between the research team, Beaufort County staff, SWMUB members, environmental groups, state agency staff, and scientists. Based on feedback from these individuals, we established the WAC to help drive the project data collection, analysis, synthesis, and translation. Through a series of four facilitated and interactive workshops as well as email contact, the strength of the project was increased. This also helped to ensure that the information collected has utility for Beaufort County. The WAC understands the limitations of the data and the potential use of the information, and have asked us to present the results to the SWMUB and Beaufort County Council's Natural Resource Committee. Over the next two months, we will first present the information associated with this final report to the WAC who will help us outline the critical information that will be most useful to the SWMUB and Natural Resource Committee.

The second major outcome for this project was the development of strong relationships between rainfall and salinity drop throughout the length of each study tidal creek and across the study creeks in WAC-selected watersheds in order to define areas where waters would be deemed more volume sensitive. This was achieved through monitoring salinity and rainfall down the length of each system via a network of 26 salinity-logging datasondes. There were six sondes deployed in each of the Okatie River, May River, and Wallace Creek watersheds, and eight placed in the bifurcated Battery Creek watershed. Each watershed was also outfitted with a weather station that included a rain gauge. The portions of each creek identified as sensitive were, inclusive of their upstream components, OK3, MR2, WC1a and WC1b, and BC2a and BC1b. The headwaters of Huspah Creek, HP2, also appeared to be very sensitive, but more data are needed to confirm this. When comparing the sensitive headwater portions across watersheds, the order of sensitivity (most to least) was found to be Huspah Creek, Okatie River, May River, Battery Creek, and Wallace Creek. The sensitivity appeared to be related to coverage of freshwater wetlands (positive), creek width (negative), coverage of estuarine wetlands (negative), and imperviousness (positive).

The third major outcome was the identification of all seventeen watersheds in Beaufort County as more or less volume sensitive. This was conducted based on the findings of the data collected and analyzed to date as well as on a watershed level assessment of the major watersheds in Beaufort County. Based on this landscape analysis, the larger coastal watersheds west and northwest of Port Royal Sound were found to be more sensitive and the small coastal watersheds east of Port Royal Sound were found to be generally less sensitive. All creeks are sensitive down to some point along their length; however, this analysis provides a perspective on which watersheds are expected to be more sensitive over more of their length. We had not originally proposed to conduct this analysis; however, we wanted to provide a broader context and better understand the potential types of watersheds in the County. Beaufort County can use this information to identify priority watersheds for consideration of stronger stormwater management requirements and in the identification of systems that warrant additional protection.

The fourth major outcome was the best management practices (BMPs) and climate change scenarios for each of the study watersheds. Beaufort County identified this as a critical component to the project. In particular, they want the scientific evidence to help decide where limited resources should be placed for mitigating the impacts from current development levels but also to understand what they might expect in the future. Ultimately, they want to keep the quality of life in Beaufort County, which for them includes healthy coastal waters and abundant natural resources.

Methods Leading to above Outcomes

Collaboration

Upon learning of funding for this project, we met with Dan Ahern (retired Beaufort County Stormwater Manager), Kim Jones (Town of Bluffton Stormwater Manager and SWMUB member), and Andy Kinghorn (SWMUB member) to discuss the proposed collaboration approach. It was decided that we would present to the SWMUB and discuss development of a technical committee. We presented the proposed project and establishment of the technical committee to the SWMUB on August 7, 2013. The SWMUB was interested in the findings of the project, and we discussed who should participate on the technical committee. This led to the establishment of the Watershed Advisory Committee (WAC) with representation from SWMUB, stormwater management professionals, natural resource or water quality managers, and active citizens. It was also requested we give a presentation to be delivered to the Beaufort County Council's Natural Resource Committee, which was conducted at their next scheduled meeting. This presentation was televised and has been shown several times on the county public affairs station.

The Watershed Advisory Committee (WAC) was established in September 2013 with the following members currently participating.

Beaufort County Watershed Advisory Committee – Stormwater Volume Sensitivities	
Dan Ahern	Retired Manager, Beaufort County Stormwater Utility
Reed Armstrong	Project Manager, South Coast Office, SC Coastal Conservation League
Russell Berry	Director, SCDHEC Environmental Quality Control Region 8
Bob Gross	Owner, Beaufort Group, LLC
Kim Jones	Director, Stormwater Management Division, Town of Bluffton
Andy Kinghorn	Member, Beaufort County Stormwater Management Utility Board
Eric Larson	Manager/Engineer, Beaufort County Stormwater Utility
Chris Marsh	Director, The LowCountry Institute
Danny Polk	Stormwater Inspector, Beaufort County Stormwater Utility
Kevin Pitts	Special Projects Manager, Beaufort County Stormwater Utility
Al Segars	Stewardship Coordinator, ACE Basin NERR
Don Smith	Chair-Beaufort County Stormwater Management Utility Board
Al Stokes	Manager, Waddell Mariculture Center
Alan Warren	Program Director, Environmental Health, USCB
ex-officio:	
Anne Blair	Project Scientist, NOAA- Hollings Marine Laboratory
John Leffler	Project Administrator, ACE Basin NERR Research Coordinator
Eric Montie	Faculty, Biology Dept., University of South Carolina – Beaufort
Robert O'Quinn, IV	Field Biologist, South Carolina Department of Natural Resources
Denise Sanger	Science Lead, South Carolina Department of Natural Resources
April Turner	Collaboration Lead, South Carolina Sea Grant Consortium
Andrew Tweel	Project Scientist, South Carolina Department of Natural Resources

Engagement of the WAC was primarily through three workshops with a fourth workshop scheduled for September 10, 2015. The first workshop was held on September 25, 2013. The focus of this workshop was largely to engage the WAC to obtain advice and assistance with the proposed study design, specifically, to identify appropriate watersheds to study, specific sites within those watersheds, and to begin discussing the modeling component and how it may benefit the study. One additional goal of this project was to ensure that the collaborative group, both the researchers and WAC, understood the project goals, and how the information generated by the project would ultimately be used. There was a thorough discussion of the project's goals, plans, and methodologies. Some of the watersheds to be studied were specified in the collaborative research MOU that pre-dated the NERRS Science Collaborative funding and were identified in the proposal. The Committee nominated and discussed additional watersheds for inclusion. SCDNR staff then surveyed and evaluated the nominated watersheds. These findings with pros and cons for each system were reported to the WAC in November via email. The WAC members considered those results and then voted on the watersheds, finally selecting two additional tidal systems, Wallace Creek and Huspah Creek for inclusion in the study. It was decided that Wallace Creek would be instrumented first with Huspah Creek being monitored if resources were available.

The second workshop was held after a significant amount of salinity data had been collected and analyzed, so that the preliminary results could be discussed, and any adjustments to methods or sites could be made. This workshop was held on September 8, 2014. Some early findings were presented, and the WAC was eager to discuss their implications and how to proceed. This process was very helpful in ensuring the development of a useful product for the group. The objectives of the September 8, 2014 workshop were to engage the WAC in facilitated discussions so that its members had a good understanding of the planned analytical approaches to the empirical data and of the structure and assumptions of the SWARM model. We also wanted to obtain advice regarding specific watershed delineation questions and site-specific modeling modifications. These discussions were designed such that the WAC members would begin to develop confidence in both the empirical analyses and the SWARM modeling approach to the extent that they would feel comfortable in making decisions based on the eventual results. A primary objective of this workshop was to get approval from the WAC of the analytical approaches to the empirical data and of the modeling methodology. This approval was forthcoming and permitted the team to move ahead with the analyses throughout the fall. In addition, the WAC raised questions about such considerations as seasonal influence and antecedent rainfall, which led to rethinking and modifying some of the empirical analyses to take these factors into account.

A third workshop was held on February 2, 2015 after a nearly a full year of data had been collected for the four main study watersheds, and considerable data analysis had been conducted. At this point there was enough data to begin the discussion about what areas could be considered volume sensitive, and where those boundaries might be delineated. With this WAC workshop, our strategy was to transfer more of the responsibility for data interpretation to the WAC with the expectation that its members would begin to accept ownership of the empirical and modeling results. The research team presented a series of representative graphs that summarized empirical and modeling results. The research team was very careful not to interpret the graphs, but just to explain how to read them. The WAC then divided into two teams and moved to separate rooms. Everyone was given three packets of graphs that related to 1) background information, 2) empirical results, and 3) modeling results, as well as a series of questions. Over the course of 90 minutes the two teams followed the questions, studied the graphs, and answered the questions to the best of their ability. Project scientists were with each team to answer specific methodological questions, but refused to interpret the graphical results with the hope that this would force the WAC members to think deeply about the results and to incorporate them into their own understanding. The teams then reconvened and, through a facilitated discussion, compared their results. Our hope was that the two groups would reach similar conclusions, and that we could identify areas where these conclusions differ. These differences then became the focus of the follow up discussion- What information do we still need? Do we need to bring in additional datasets or variables? How confident are we in these results? At the end of the workshop, the two groups rejoined and discussion addressed these and other questions. The members of the WAC asked for further monitoring to capture additional large rain events, as well as some additional analyses such as rate of change of estuarine salinity as a result of stormwater influx. We evaluated using a rate of change metric with little success in increasing the modeling performance. They also suggested that some of the monitoring sondes be withdrawn from certain locations and try to continue monitoring for large rain events. This proved very helpful to the project researchers, who followed up the workshop with a 3.5 hour meeting to consider and address all suggestions and observations developed through the WAC workshop.

We are planning an additional WAC meeting for September 10, 2015. The goal of this meeting will be to discuss this report (including the additional analyses they requested) to ensure that they can take the lead in interpretation, and to focus the discussion primarily on how they will use the results to develop new policies regarding stormwater management in the County. In addition, a second goal is to discuss how to best present the research findings and conclusions to the SWMUB and Natural Resource Committee. We believe the input received from the WAC will allow us to insure the information is translated and conveyed such that it can be used by decision makers and elected officials. We are scheduled to present to the SWMUB on September 30, 2015 and the Natural Resource Committee on October 1, 2015.

Applied Science

The geography of Beaufort County, South Carolina, is characterized by broad expanses of wetlands (43% of coastal watersheds), gently sloping topography (< 0.5 m/km in some areas), a large tidal range (2.3-2.6 m), and a dominance of soil types classified as poorly draining. In the past several decades, Beaufort County has experienced rapid population growth and the associated conversion of upland habitats to impervious surfaces, and this growth is expected to continue (Figure 1).

A variety of tidal creeks drain the upland habitats and developed areas. Excessive runoff from the proliferation of impervious surfaces has raised concern over the health of these tidal creeks. Newer housing developments have included stormwater ponds in their design as an attempt to mitigate this increase in runoff by retaining stormwater and allowing infiltration to groundwater and slower release to downstream systems.

Due to the low gradient and high tidal exchange, many of the creek systems are intertwined with watershed boundaries that are difficult to define. However, we were able to define 17 watersheds that originate near or within Beaufort County (i.e., not fed by riverine flows from beyond the coastal zone) (Figure 2). We focused on these low-lying coastal headwaters to study the varying responses to stormwater runoff and identify sensitivity thresholds.

The average size of these watersheds was 85 km^2, and five watersheds were selected to use for this volume sensitivity study. Beaufort County and the WAC-selected watersheds that were a priority area for mitigative measures and reasonably representative of other watersheds in the county, but that also represented a range of variables to help identify the dominant characteristics related to volume sensitivity. These systems were initially the Okatie River, May River, Battery Creek, and Wallace Creek, with Huspah Creek added later (Figure 3). Land use, soil types, and other geophysical characteristics of these watersheds are discussed in greater detail in the watershed study as part of this project.

In total, 26 salinity-logging datasondes were deployed in four priority watersheds of varying size, development proportions, and marine influence for at least a year to assess the variability in salinity response to stormwater input. An additional two months of data have been collected at a fifth watershed (Huspah Creek) with six datasondes, and this monitoring is ongoing with funding support from Beaufort County. Each watershed was also outfitted with a data logging rain gauge.

Sampling sites in each creek system were established from the headwaters to a downstream location that extended into what was expected to be volume "insensitive" waters. The downstream location was identified based on previously collected data provided by the South Carolina Department of Health and Environmental Control (SCDHEC) such as shellfish bed harvesting classification change (e.g., restricted to open), an indication that the system is no longer volume sensitive (Figure 4). There were six sondes deployed in each of the Okatie River, May River, and Wallace Creek watersheds, eight placed in the bifurcated Battery Creek watershed, and later six sondes placed in Huspah (Figure 3). Figure 5 shows an example of the rainfall and salinity data collected from OK1 (headwater site) and OK6 (most downstream site).

At each site, a HydroLab MS5 salinity/temperature/depth data logger was installed near the bottom of the water column to ensure that they remain submerged even during the lowest spring tides. Data sondes took measurements at 30 minute intervals. The water quality dataloggers followed QA/QC procedures similar to those employed by the NERR System-wide Monitoring Program (SWMP) to ensure the instrumentation functioned properly in the field and that all units and parameters were within the manufacturer's recommendations (Small et al. 2010). Rain gauges were installed at a central location in each watershed, and it was assumed that this rainfall would represent rainfall for the entire watershed.

Our primary metric of volume sensitivity was the drop in salinity following a rain event (Figure 6). Although we tested and discussed other metrics, this proved to be the most useful. Measurements of time from rain event to maximum salinity drop often took several days and were confounded by additional rain events. We removed the tidal signal prior to analysis by applying the Palmetto Filter, a nested 13.5 h moving window average (MWA) and a 25 h MWA developed by Paul Conrads (USGS, 4/22/2008, personal communication), because we were interested in characterizing the salinity changes over a longer time period than a single tidal cycle (Figure 6). The salinity drop was then measured in response to each rain event using the filtered data (Figure 7).

We defined a 'rain event' as occurring on a day (or days) with consecutive rainfall. It was necessary to condense the half-hourly rain data into a larger unit of time because salinity drops occurred over a period of days in many cases. If rain data were analyzed at a finer resolution, it would be impossible to attribute a salinity drop to a rainfall amount. In this regard, compressing rainfall into a timescale of days, rather than hourly increments, was most appropriate given that the salinity drops also occurred over a number of days. Accordingly, consecutive days experiencing rainfall were counted as one event, with a full day of no rainfall being necessary to end an event.

Once the salinity drops for each rain event were quantified, these two variables were entered into regression models for each site with rain as the independent variable and salinity drop as the dependent variable. These relationships were tested for significance, and their slopes were studied in greater detail, with higher slopes indicating a greater salinity response, or more sensitivity, for a given rainfall event. These slopes were then used to compare between watersheds and identify differences in volume sensitivity.

These subwatershed slopes were also used to look for factors that could help explain differences in salinity drops. A number of additional watershed characteristics, such as land cover classes and watershed size, were explored using stepwise multiple polynomial regression. Variables expressing curvilinear relationships to the slope were entered as such in the model.

To further explore these salinity-rainfall relationships, a study was conducted to investigate characteristics of watersheds originating in or near Beaufort County (Figure 3). US Geological Survey (USGS) Hydrologic Unit Code (HUC)-12 watersheds served as our basis for identifying the major creek/river systems. A variety of land use/land cover, soil type, and geophysical data were collected for each watershed using ArcGIS 10. These were then compared between all of the watersheds to identify how the study watersheds compare to other watersheds not included in this study. Multiple regression was used to quantify these relationships, and to draw inferences about the sensitivity of other watersheds in Beaufort County based on similarities and differences to the five watersheds with known sensitivities.

The Stormwater Runoff Modeling System (SWARM) was used to model runoff for each of the study watersheds and sub-watersheds. SWARM is based on the long-established and widely-used runoff curve number and unit hydrograph methods of the US Department of Agriculture, National Resource Conservation Service (USDA, NRCS), and has been calibrated for the low-gradient topography of the Southeast coastal plain. The modeling system integrates land use, soil type, area, elevation, and precipitation amount and distribution to calculate runoff volume and runoff rate over time for individual storm events (Figure 8). Detailed descriptions of SWARM methods and applications are available in two publications by Blair and colleagues (2014a, 2014b).

The watersheds varied greatly in characteristics that affect runoff modeling such as area, level and type of development, and soil types. Because the watersheds differ greatly in area, our modeling provided both actual runoff volumes and rates as well as normalized results in order to remove effects of area. We used the actual output to investigate impacts of various drivers of runoff within each watershed and the normalized output to compare those impacts among the watersheds.

We modeled runoff for two different synthetic rainfalls: 1.95 inches, which is the 95th percentile 24-hour rain for the region and 4.5 inches, which is the 24-hour 2-year storm event for the general area. For the hydrographs, we also can use actual rainfall amounts and distribution recorded by rain gauges in each of the watershed.

We developed regression equations for each watershed by calculating volume from rainfalls of 0.5 inch to 5 inches using 0.5 inch intervals (Table 1). For each site watershed, these equations can predict runoff for any rainfall amount, and we used them to predict runoff for each of the rainfall amounts connected to specific drops in salinity in order to then use the predicted volumes as regressors and the salinity drop values as the response variables.

Because SWARM output showed statistical significance in predicting salinity changes, we selected the 6 subwatersheds designated as critically sensitive to stormwater runoff and used SWARM to model their responses to the implementation of a volume-control BMP scenario, two buildout scenarios, and two climate change scenarios.

For the BMP scenario, the objective was to set the watershed hydrology to one of low development. We modeled runoff using the 95th percentile rain amount of 1.95 inches and adjusted land-use categories in each watershed to reflect a development level of 9% impervious cover. Ten percent impervious cover is considered to be the threshold for stream/creek quality degradation (Schueler 1994, Holland et al. 2004, Sanger et al. 2015). The modeled volume at 9% impervious cover serves as the target for volume reduction required for current levels of development. Additionally, we adjusted land-use categories in each watershed to reflect two higher levels of development: 50% Build Out and 100% Build Out. Fifty percent Build Out is projecting additional watershed development for half of dry land not yet developed. One hundred percent Build Out projects additional watershed development for all dry land not yet developed. The difference between the low development volume and the volumes for the 3 higher development levels shows the amount of volume reduction required for each watershed to return to a low-development hydrology.

For the climate change scenarios, we based our modeling on general predictions of increasing frequency and intensity of heavy storms (Gutowski et al. 2008). Already from 1958 to 2012, the heaviest storm precipitation increased by 27% in the southeast US (Melillo et al. 2014). We compare watershed runoff using average antecedent runoff condition (ARC) to runoff from two different climate scenarios: Climate 1 and Climate 2. Both climate scenarios include a 15% increase in precipitation. Climate 1 uses semi-wet ARC and Climate 2 uses wet ARC. ARC comprises “rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, state of growth, and temperature” (USDA NRCS 2004) and has a strong impact on both volume and rate of runoff.

Data Leading to Above Outcomes

Review of existing and new rainfall data

Rainfall during 2014 and 2015 compares well to rainfall data collected by Ashepoo-Combahee-Edisto Basin National Estuarine Research Reserve (ACE Basin NERR) meteorological station (station ID: ACXS1) on both monthly and annual timescales. The typical peak in rainfall occurs in the summer months, as weather patterns are dominated by late afternoon air mass thunderstorms associated with heating of the land surface (Figure 9A). Winter and spring monthly precipitation is about half that of summer patterns, but generally occurs associated with frontal systems that result in a more homogenous distribution of rainfall. April 2014 resulted in a very large rain total (221 mm) which is over three times the long term (2001-2014) average of 65 mm. Summer 2014 precipitation, which usually peaks in August, peaked in September instead, and was again above average. To date, 2015 has been a fairly average precipitation year, staying near 1 standard error (S.E) from the long-term average. On an annual basis, 2014 was the wettest year since 2001, when data collection began, for the ACE Basin NERR station (Figure 9B).

In addition to producing the most precipitation, August also experienced the shortest average time between rain events—3 days (Figure 9C). November had the least frequent rain events, averaging 7.8 days between events. Another interpretation of this data is that rain events in August were more likely to occur on wetter soils than those in November, not accounting for differences in evaporation or other seasonal effects.

Rain data collected for this study reflect the same seasonal trends as the ACE Basin NERR station. However, on a per-event basis, there tended to be fewer, larger events occurring in the fall and winter months (Figure 10A). There was good agreement between the study watershed gauges, and this agreement was stronger for the larger frontal events than the summer-pattern rain events. The vast majority of rain events captured were less than 10 mm total, with exponential decay towards the larger events (Figure 10B). The average rain event was 34 mm (1.3 in), and the maximum observed was 131 mm (5.2 in).

Coliform data

We reviewed fecal coliform data collected in Beaufort County by the SCDHEC. There was high interannual variability (Figure 11A), as well as high spatial variability. Exceedances, defined as counts in excess of 40.9 cfu/100 ml, were computed on an annual and monthly basis. On average, nearly 4% of samples collected exceed this threshold, and there was no clear relationship to precipitation totals on an annual basis; however, there may be stronger relationships if investigated at a finer temporal resolution. November data indicated the highest exceedances, and January through March were the lowest (Figure 11B). There may be a sampling bias, and we did not have the necessary information to correct for this.

For the four main study watersheds, we summarized coliform data relative to our study subwatersheds. The headwater portions of these systems generally experienced much higher coliform counts than samples collected farther downstream in the same systems (Figure 12). No headwater trend was observed in Wallace Creek, which only contains two sites compared to the nine and ten sites of the other watersheds. Wallace Creek is also the least developed of the study watersheds, and among the least developed in the County.

Salinity data

Nearly 750,000 salinity readings were collected across five watersheds comprised of 32 subwatersheds, capturing 791 salinity responses to rain events over the course of the project. These sites exhibited wide variation in almost every attribute we considered, including soil type, land-use characteristics, and geophysical setting. The average salinity for all data collected was 27.3 psu, with individual site averages ranging from 14.2 (OK1) to 32.3 (WC5).

The average rain-induced drop in tidally-filtered salinity was 2.8, with a maximum observed drop of 23 psu in the Okatie River headwater site (OK1) following a 4 day rain event in November 2014 that resulted in 128 mm of precipitation. Figure 13 shows an April 18, 2015 rain event that dropped similar amounts of rain for the primary four systems.

In terms of volume sensitivity (i.e., the response of a receiving body to an input of stormwater), we found the drop in salinity to be most informative (Figure 14). Average salinity drops for each site are shown in Figure 15. Specifically, we compared the rainfall total to the observed drop in salinity for each of the 791 site-events, and formed regression relationships for each of the 32 subwatersheds. These relationships are shown in Figures 16 through 20. Summary statistics for these regressions are shown in Table 2. The slope of these relationships (unless stated otherwise, 'slope' refers to this relationship) proved to be a useful metric for volume sensitivities—higher slopes corresponded to a greater drop in salinity for a given rain event. The greatest slope, a drop of 0.14 psu per mm rainfall, was initially observed in the headwaters of the Okatie River. Towards the end of the study, when Huspah Creek was instrumented in June 2015, much higher salinity drops were observed (slope = 0.27), suggesting even greater sensitivity to volume inputs. There were, however, only 5 events observed in the Huspah Creek headwaters versus 41 events for the Okatie River headwaters, and this relationship may change as more data are collected.

A comparison of these slopes and their standard errors is shown in Figure 21. Least squares means differences (LSD) were used to look for thresholds and significant differences in subwatershed responses to volume inputs. These LSD t-tests are presented in Table 2. It was clear early in the study that the Okatie River and May River headwater sites were quite different from Battery Creek and Wallace Creek in terms of salinity response to rain events, with slopes approximately double that of the other two creek headwaters.

The time to achieve minimum salinity following a rain event was also measured. From this we calculated the salinity drop over time of this trend (salinity drop per unit time). However, these relationships were much noisier and were not helpful in assessing volume sensitivity for these watersheds during this study period. These results are not presented.

Predictive model

The rainfall-salinity drop relationship slopes were used to compare among subwatersheds and explore a variety of land cover and geophysical characteristics that may help explain the observed sensitivity differences. A scatterplot matrix of these relationships is shown in Figure 22. Additional variables were explored, but are not shown, such as coverage of specific soil types (e.g., "poorly drained"), forested upland area, or developed land use. Huspah Creek sites, with much fewer data to support the slope relationships, are shown in grey. These sites were quite different in terms of width, distance to bay, estuarine wetland coverage, and provided a good opportunity to test previous observations and relationships.

A multiple polynomial regression was used to quantify the relationship between a subset of these independent variables and the slopes identified from the regressions of rainfall and salinity drop for each of the subwatersheds. The three lower Huspah Creek sites were excluded due to poor relationships between rainfall and salinity drop, which may be attributable to low sample size. Battery Creek 1a was also excluded due to its very small size (10% of the next closest subwatershed) that was discerned when watershed boundaries were reanalyzed using LiDAR elevation data rather than boundaries derived using more conventional means.

As can be seen in the scatterplots, some of these relationships to slope were non-linear (Figure 22). These were fit accordingly in the multiple regression. The results of this regression are shown in Figure 23 and Table 3 ($r^2 = 0.95$, $F_{(6, 21)} = 70.64$, $p = <0.0001$). The percent cover of freshwater wetlands (excluding water) exhibited the strongest relationship to slope, followed by creek width and estuarine wetland coverage. Percent imperviousness (a combined metric of soil and development-related imperviousness) was also significantly inversely correlated to slope. Residuals from this model followed a normal distribution (Shapiro-Wilk: $p = 0.45$). The root mean square error from this predictive model is 0.016 psu per mm rain.

Watershed study

Valuable comparisons were made between our 5 study watersheds and 12 other nearby watersheds (Figure 2). A wide variety of data pertaining to these watersheds were collected, including land use and land cover characteristics (Table 4), soil classifications and coverages (Table 5), and additional geophysical parameters (Table 6). These tables are color-coded to help depict variability and common attributes between the watersheds.

Broad Creek, Battery Creek, and Albergottie Creek were the three most developed watersheds. Not surprisingly, the larger watersheds toward the head of the estuary were comprised of the largest coverage of freshwater wetlands. The watersheds monitored for volume sensitivity (in bold) represent a wide range of variability for nearly all of these parameters. The addition of Huspah Creek to the monitoring database provided an even greater coverage of this variability, especially due to its low abundance of estuarine wetland and corresponding high coverage of freshwater wetland. As noted earlier, Huspah Creek also exhibited a much higher slope than any of the watersheds studied prior to its introduction.

Stepwise multiple regression was used to identify parameters best correlated to the slope values. We also included average salinity drop (the average of the observed drops for all rain events) in this analysis. Due to the low sample size ($n = 5$ watersheds), we tested several models ranging from simple univariate to the maximum possible given the sample size, a multiple regression of three independent variables. The results of these models are presented in Tables 7 and 8. Because the very high correlations ($r^2 = 0.999$) may be overfit due to the low sample size, we present an array of tests of increasing complexity (and increasing potential for type I error).

Variability in slopes was best explained by an inverse relationship to the coverage of estuarine wetlands (Table 7). The second most explanatory variable was a positive correlation to the coverage of soils classified as ‘very poorly drained.’ The full model also included freshwater wetland coverage.

Variability in average salinity drop was somewhat different, with area (km^2) explaining much of the variability—the larger watersheds (Okatie and May Rivers, as well as Huspah later on) tended to contain the most sensitive headwaters (Table 8). The addition of coverage of poorly drained soils further improved this model. The full model also identified creek width at mouth as a helpful independent variable. Predicted slopes and average salinity drops are shown in Table 9.

We used this suite of models to estimate headwater sensitivity of the 12 coastal watersheds not monitored for salinity sensitivity in this study. To synthesize these model results, such that the result is not dependent on a single model, but rather consistency between varied models that utilize different parameters, we selected the top (most sensitive) and bottom (least sensitive) 25% from each model. We then assigned a total score to each of the watersheds, with a value of 3, for instance, corresponding to that watershed appearing in the top 25% for 3 of the 6 models. A value of -6, for instance, would mean that all six models predicted sensitivity in the bottom 25%.

According to this classification scheme, 7 of the 17 watersheds were modeled to have sensitive headwaters. Scores within these categories, however, do not necessarily indicate more sensitivity, but rather more model confidence in the prediction. These included, in decreasing order: the Pocotaligo River (5), Euhaw Creek (4), Okatie River (3), Wright River (3), Huspah Creek (3), Tulifiny River (3), and Chechesse River (2). Six watersheds were identified as least likely to be sensitive, and these were, in order: Wallace Creek (-6), Village Creek (-5), Albergottie Creek (-3), McCalleys Creek (-3), Morgan River system (-3), and Boyd Creek system (-3). Actual estimates of sensitivity would best be determined from individual models and these are presented in Table 9.

Stormwater runoff modeling results

Table 10 provides details for major watershed characteristics related to modeling runoff. Two of the major drivers of stormwater runoff are development level and soil type. Development changes the hydrology of a watershed by creating surfaces impermeable to rain, thus causing more rainfall to be converted to runoff. Soils range from those pervious to rainfall to ones that rainfall cannot penetrate. Two watersheds in Battery Creek had the highest percentage of developed land use – BC2a with 57% and BC3a with 47%. The lowest percentage of developed land use was in Wallace Creek where the six watersheds range from 1% to 7%. The most impervious soils were found in the Okatie River with all six watersheds at 90% to 92%. May River was next with an impervious soil range of 72% to 78% for the six watersheds followed by Wallace Creek with a range of 60% to 70%. Battery Creek had the lowest proportion of impervious soils with a range of 27% to 61%. Watersheds absorb an initial amount of rainfall before runoff begins, and that amount is referred to as the initial abstraction (I_a). For the four major watersheds, the I_a ranged from 0.19 inches to 0.35 inches. Okatie River watersheds had the lowest range owing to the combination of high development and impervious soils – 0.19 inches to 0.21 inches. Wallace Creek watersheds had the highest range owing to low development and soils around 65% impervious – 0.26 inches to 0.35 inches.

We modeled runoff for all of the watersheds based on a 4.5 inch 24-hour rain event (Figures 24 and 25). Volume increased with progression from the headwaters to the final watershed outlet for each of the four main waterways as expected since each subsequent watershed had greater area than the preceding ones. Runoff for the two smaller waterways, Wallace Creek at 1944 hectares (ha) and Battery Creek at 3,229 ha, totaled 762 acre feet (af) and 1,332 af, respectively. (An acre-foot, af, is the volume of water required to cover an acre at a depth of one foot.) Runoff for the two larger systems, Okatie River at 4,859 ha and May River at 6,093 ha, totaled 2,222 af and 2,509 af, respectively.

When runoff is shown as a percentage of the rainfall that was converted to runoff, the results showed similarity for the Okatie River and Wallace Creek subwatersheds. MR1b was higher than the other May River watersheds and was also the most highly developed. BC2a was the highest of the Battery Creek watersheds and was also the most highly developed.

We constructed hydrographs for the watersheds in each of the four waterways to show runoff rate over time. As with the modeled volume, rate and time increased with progression from the headwaters to the final watershed outlet. For the Battery Creek hydrographs, the peak rate ranged from 9 cubic feet per second (cfs) and 102 cfs at the two headwater watersheds to 757 cfs at the final outlet (Figure 25). When the hydrographs were normalized to show cfs per square mile in order to remove the effect of area, BC2a had the highest peak rate followed by BC1a and then BC3a.

To project the potential impacts that implementation of volume-control BMPs and changing precipitation patterns from climate change might have on runoff volume in priority watersheds, we conducted a series of scenarios using SWARM. SWARM scenarios included: (1) pre-development scenarios to understand what volume reduction would be required in the developed watersheds to reach pre-development levels (< 9% impervious cover); (2) future development scenarios to understand the increase in volume associated with increased development levels; and (3) two climate change scenarios to understand how the predicted future weather (i.e., increased rainfall and wetter soils for periods of time) will change the runoff volume for the study watersheds.

For the BMP scenario of identifying the volume reduction amount required to match a low development (9% impervious cover) hydrology for a 95th percentile rain of 1.95 inches, three of the six volume sensitive watersheds were already below the low development level and were not considered (Table 11). For the others, BC2a needed to reduce volume from 30 af to 14 af, OK3 from 266 af to 221 af, and MR2 from 408 af to 398. BC2a had the greatest relative change.

Modeling impacts of additional development in each watershed showed the greatest relative changes for the lower developed watersheds of WC1a, WC1b, and BC1b (Table 11). At the 50% Build Out, runoff volume increased by 46%, 35%, 44%. At the 100% Build Out, volumes increased by 112%, 82%, 104%. For the higher developed watersheds of BC2a, OK3, and MR2, relative increases were lower: 23%, 11%, 20% for the 50% Build Out; 57%, 22%, 45% for the 100% Build Out. Volume increases for the larger watersheds, OK3 and MR2, were an order of magnitude greater than for the smaller ones. For all of the watersheds, the two development scenarios result in an increase in the targeted volume reduction required to achieve a 9% impervious cover hydrology.

We constructed hydrographs for the most developed small (BC2a) and large (OK3) watersheds to investigate the impact of development on the rate of runoff (Figure 26). To retrofit the watersheds to the lower development hydrology, for BC2a, the peak rate would need to decrease from 27 cfs to 12 cfs for the 1.95 inch rain and from 122 cfs to 73 cfs for the 4.5 inch rain. For OK3, the peak rate would need to decrease from 115 cfs to 97 cfs for the 1.95 inch rain and from 472 cfs to 423 cfs for the 4.5 inch rain. OK3 rates were much higher than BC2a because of the watershed's larger area – 2,296 ha compared to 288 ha; however, the relative change in rates was much greater for the smaller watershed, which could be partially explained by its more pervious soils.

The climate scenarios applied to the modeling of a 1.95 inch rain resulted in remarkably large increases in runoff volume (roughly double) for all watersheds (Table 12). For the Climate 1 scenario of a 15% increase in rainfall and a change from average to semi-wet antecedent runoff conditions, volume increases were greatest in the less developed watersheds (WC1a, WC1b, BC1b) at 108%, 106%, 107%. In the more developed watersheds (BC2a, OK3, MR2), volumes increased by 83%, 77%, 88%. For the Climate 2 scenario which included a 15% increase in rain and a change from average to wet antecedent runoff conditions, volume increases were generally double those of the Climate 1 scenario. For less developed WC1a, WC1b, BC1b, volumes increased by 223%, 212%, 222%, respectively. For more developed BC2a, OK3, MR2, the increases were 157%, 143%, 172%, respectively.

As with the BMP and development scenarios, we constructed hydrographs for the most developed small (BC2a) and large (OK3) watersheds to investigate the impact of climate on the rate of runoff (Figure 27). For BC2a at the 1.95 inch rain, the peak rate increased 93% (from 27 cfs to 52 cfs) for Climate 1 and 178% (to 75 cfs) for Climate 2. For the 4.5 inch rain, the peak rate increased 57% (from 122 cfs to 191 cfs) for Climate 1 and 95% (to 238 cfs) for Climate 2. OK3 rates were much higher than BC2a because of the watershed's larger area – 2,296 ha compared to 288 ha. For the 1.95 inch rain, the peak rate increased by 78% (from 115 cfs to 205 cfs) for Climate 1 and by 144% (to 281 cfs) for Climate 2. For the 4.5 inch rain, the peak rate increased by 49% (from 472 cfs to 705 cfs) for Climate 1 and by 78% (to 839 cfs) for Climate 2.

Data Summary and Context

The two primary study years, 2014 and 2015, proved to be good examples for studying the effects of storms. From a stormwater perspective, 2014 experienced higher than average precipitation, which provided a large number of rain events to follow as the stormwater pulse travels through each system. To date, 2015 was more reflective of an average rainfall year for this area. Together, these two years have provided a good variety of events to study.

We collected nearly 750,000 salinity readings across five watersheds, capturing nearly 800 salinity responses to rain events over the course of the project. For each rain event, we measured the salinity drop that occurred at each site. By compiling a large database of these rain events, and the response in the tidal creeks, we were able to identify areas that were volume sensitive. The most volume sensitive areas experienced the greatest salinity drop for a given rain event, and we were able to establish relationships between rainfall amount and projected salinity drop, and thus identify salinity sensitivity thresholds within each watershed.

Using feedback generated at one of our WAC workshops, we were able to delineate volume sensitive cut-points in each of the four main study watersheds. These were largely based on the slopes of the relationships between rainfall and salinity. Because each watershed responded quite differently to rain inputs, and with some watersheds being much more variable than others, there was no set threshold for what we defined as "sensitive," rather we identified salinity sensitivity thresholds based on a holistic assessment of all sites in each system. With a majority of agreement from the WAC, we identified watersheds as "sensitive," with the caveat that some of the choice in location was limited by the spatial resolution of the deployment zones—i.e., we cannot feasibly instrument every portion of a system. These watersheds were, inclusive of their upstream components, OK3, MR2, WC1a and WC1b, and BC2a and BC1b. We erred on the side of inclusion, rather than exclusion, in that if a site was transitional it was included as sensitive. For instance, the two most headwater sites in the May River, MR1a and MR1b, exhibited high sensitivity (mean slope = 0.125), yet the next site after the confluence of these two branches exhibited moderate sensitivity (slope = 0.060). Therefore, there was likely continued sensitivity beyond the first two sites, and so we included the watershed downstream, MR2. The mean of the slopes of all cut points was 0.060 psu/mm rainfall, which may serve as a general guideline based on the watersheds studied and rain events captured to date. A more objective classification of the slope breakpoints for each watershed is the least squares differences test. These results were very similar. The main distinction was that Wallace Creek, the least sensitive and least developed watershed, did not contain large enough differences in salinity drop to be statistically significant between the headwaters and downstream portions. This was likely due to the low levels of development and more pervious soils.

Expansion of the salinity monitoring into Huspah Creek proved to be worthwhile, in that it tested much of what we knew, and expanded the range of site types in the study to include more brackish salinities. Based on early results (5 rain events) salinity drops in Huspah Creek were more than twice those of the Okatie River headwaters for the same amount of rainfall.

Once we had identified volume sensitive portions of the study watersheds, we began to look for factors correlated to this sensitivity and also to model how these watersheds might respond to implementation of volume control BMPs or changing precipitation patterns associated with climate change. We used a statistical model to look for variables most closely associated with volume sensitivity. The most significant variable correlated to volume sensitivity was percent coverage of freshwater wetlands. Areas with higher percent coverage of freshwater wetlands were more likely to be volume sensitive. Two variables were inversely correlated to volume sensitivity: creek width and coverage of estuarine wetlands (salt marsh), and so volume sensitivity decreased with increases of these metrics. This was not surprising, as estuarine wetland coverage and creek widths increase toward the downstream section of these watersheds.

Imperviousness, a combined metric we developed to account for both soil type and land-use categories, was also significantly positively correlated to volume sensitivity. We used this prediction formula to estimate changes in slope that might occur in response to changes in imperviousness. This metric weighs development that occurs on pervious soil greater than development occurring on an already impervious soil surface. We estimated the change in slope in response to an increase in 10% of the total imperviousness score for all five headwater sites, presented as *current slope (predicted slope)*: Okatie River 1: 0.13 (0.16), May River 1a: 0.12 (0.15), Battery Creek 2a: 0.06 (0.08), Wallace Creek 1a: 0.06 (0.07), Huspah Creek 1: 0.27 (0.31). A 10% increase in imperviousness would result from 10% of the remaining undeveloped upland of a pervious soil type being developed as C-CAP development class high, medium, or low intensity.

To provide a broader context for our research, we investigated other coastal watersheds within Beaufort County, and quantified a variety of land cover, soil type, and geomorphological characteristics at a coarser spatial scale than the detailed subwatershed comparisons made above. This provided an opportunity to compare our study watersheds to other watersheds we did not study, and to make inferences about their potential headwater sensitivities. This statistical modeling identified a number of variables related to volume sensitivity, and some of these varied between models. There was high covariability between these variables, and so we let stepwise regression identify the greatest correlations.

Of the 17 watersheds studied here, the models identified 7 that were likely to contain volume sensitive headwaters. In general, these tended to be in the west and northwest of Port Royal Sound, which are also the larger coastal watersheds in this area: Pocotaligo River, Euhaw Creek, Okatie River, Wright River, Huspah Creek, Tulifiny River and Chechesse River. Watersheds identified as least likely to contain sensitive headwaters were, in general, smaller and concentrated on the eastern side of Port Royal Sound. These watersheds were Wallace Creek, Village Creek, Albergottie Creek, McCalleys Creek, the Morgan River System, and the Boyd Creek System. With the exception of the Wright River and the Boyd Creek System, these are all located on the Sea Islands in the vicinity of Beaufort. The absence of the May River and Battery Creek from these lists indicates that they did not appear in the top 25% of sensitive or insensitive for any of the models. The WAC did, however, identify sensitive areas within both of these watersheds.

SWARM provided modeled runoff volume for all of the study watersheds in each of the four creek systems. This provides basic data on the percent of development, percent of impervious soils, and amount of rainfall required in order for runoff to occur under average conditions. It also provides the actual runoff modeling which allows for comparison between the watersheds of each creek system. In addition, the normalization of the runoff (both volume and rate over time) by area allows comparison among all of the watersheds, with charts and hydrographs enabling identification of any anomalies to investigate further. A regression equation for each watershed was developed to allow Beaufort County to predict the runoff volume based on any selected rainfall amount.

To project the potential impacts that implementation of volume control BMPs and changing precipitation patterns from climate change might have on runoff volume in priority watersheds, we conducted a series of scenarios using SWARM. The six headwater watersheds designated as critically sensitive to stormwater runoff were used for modeling the responses to implementation of mitigation measures in the two more-developed watersheds scenario, two volume-control BMP scenarios, and two climate change scenarios.

For the BMP scenarios, the first objective was to set the watershed hydrology to one of low development. Three of the six watersheds had levels of development lower than the targeted level (9% impervious cover). With the three more-developed watersheds, volume reduction amounts required to reach the targeted amount were calculated. The volume reduction for Battery Creek to achieve 9% impervious cover would require a 53% reduction, in comparison to the May River and Okatie River which only required a 2% and 17% reduction, respectively.

Volume reduction amounts were calculated for two higher development scenarios for all six watersheds. Volume increases for the larger watersheds, OK3 and MR2, were an order of magnitude greater than for the smaller ones. Using the current development level and the two higher levels will allow Beaufort County to have an understanding of what stormwater runoff volume changes are likely as development continues.

For the climate scenarios, we based our modeling on general predictions of increasing frequency and intensity of heavy storms. Both scenarios used an increase in rainfall, and each scenario included a wetter antecedent runoff condition. In general, the runoff volume doubled or tripled within each system for the two scenarios.

Our stormwater runoff modeling provides Beaufort County with information and insights concerning runoff in the study areas and how it will be impacted by additional development and by climate change. There is also the potential to apply SWARM to other creek systems both to calculate runoff and to predict salinity changes. However, as with all modeling, SWARM output should be viewed as an approximation of actual runoff. SWARM's validations indicate that the major drivers of runoff are captured well in the modeling system, but the results are best viewed as representative of runoff for a given rain event.

Going Forward

Although we have collected data in five watersheds in Beaufort County, there is still much that is unknown with regard to volume sensitivity. This is evidenced by our recent data collection in the Huspah Creek watershed, which varied considerably from the other watersheds studied. Had we used a regression model built on the four primary study watersheds, the large salinity drops observed in Huspah would have been grossly underpredicted. This realization confirmed that there were still a number of unknowns. We would continue to study these salinity responses, but we would use the watershed study database to identify areas where little is known with regard to volume sensitivity. Additional data collected in these relatively unstudied watersheds could then be used to validate or test the models presented here. We will discuss this with the WAC at our next meeting.

The original proposal also included a series of bioassays to assess the impact of these salinity drops on various biota of concern. Due the complexity and resources needed to complete these types of studies, this was withdrawn from the proposal. It is, however, still of interest to us and the WAC. Given additional resources we would pursue a targeted series of bioassays designed to assess the effects of stormwater runoff on estuarine organism health and survival.

Retrospective

Challenges

Overall, the project has been successful. As with other research projects, there were some challenges. The design, acquisition, and deployment process proceeded slower than anticipated. Although the official start date for the NERRS Science Collaborative grant was September 1, 2013, until the necessary forms were signed by all parties and the account was set up, it was October 22nd before we were permitted to bid out the equipment, and early December before our partner, the University of South Carolina-Beaufort received its subcontract. As a result, the sondes and rain gauges that had to be purchased did not arrive until December. By borrowing existing equipment we were able to completely outfit the Okatie River watershed and to use other sondes to survey the tidal dynamics in other watersheds. Considerable effort was made to contact dock owners in each waterway, explain the purpose and requirements of the monitoring work, and securing their cooperation in deploying monitoring sondes or weather stations from their docks. By the end of February 2014, the Okatie River, May River, Battery Creek, and Wallace Creek were fully instrumented, and we were prepared to deploy in a fifth watershed.

In Huspah Creek, technical problems with datasondes delayed full deployment until the four priority watersheds could be studied for at least one year. We experienced some significant instrumentation malfunction problems during the initial deployments, particularly in Huspah Creek starting in May 2014. Datasondes were not recording correctly, and some of these malfunctions required the instruments to be sent back for repairs. We therefore made the decision to withdraw from Huspah Creek temporarily to ensure that we had enough sondes in reserve to compensate for any malfunctions in the other watersheds.

Intended User Impact on Applied Science

Intended User collaboration was an integral component of this project and contributed greatly to its success. To ensure that our analysis was as relevant and useful as possible, we actively engaged the WAC at several points along the way, via a series of interactive workshops. This group consisted of 15 individuals representing Beaufort County stormwater staff, SWMUB members, environmental groups, state agency staff, and scientists. We presented our most recent findings and gathered group feedback as to how to proceed. Therefore, the modeling, analyses, and results were strongly driven by the interests and needs of this group. This proved an invaluable resource, as the scientific process became adaptive to the information needs of the user groups. The end result, hopefully, is that by maximizing the utility of the results to Beaufort County, local stormwater managers can make the most informed decisions.

We will continue to work with the WAC beyond the ending of this grant, in accordance with our five-year Agreement. We are planning an additional WAC meeting on September 10, 2015. The goal of this meeting will be to discuss this report (including the additional analyses they requested) to ensure that they can take the lead in interpretation, and to focus the discussion primarily on how they will use the results to develop new policies regarding stormwater management in the County. In addition, a second goal is to discuss how to best present the research findings and conclusions to the SWMUB and Natural Resource Committee. We believe the input received from the WAC will allow us to insure the information is translated and conveyed such that it can be used by decision makers and elected officials. We are scheduled to present to the SWMUB on September 30, 2015 and the Natural Resource Committee on October 1, 2015.

Budget and Resources Assessment

The budget was generally sufficient to conduct the study as proposed. We were successful at collecting over a year of data for each of the four primary study systems. A portion of the success can be attributed to the purchase of the Hydrolab datasondes at a discounted price. The project has sparked a number of additional avenues to follow which we will try and accomplish with other funding sources.

What We Know Now

There were a number of bumps in the road for this project including slow purchasing due to agency software upgrades, and the inability to test the modeling system to specific sites in Beaufort County. The slow purchasing and grant establishment were out of our control. The collection of flow data for model testing was not as successful as we originally proposed. The overall time it took to collect and process the salinity data resulted in less time to measure flow at appropriate sites (i.e., locations with no overbank flow). However, SWARM modeling has been validated prior to this study using data from other estuarine tidal creeks in South Carolina. We are currently working with Beaufort County to collect paired data in the Okatie River. The County purchased a similar instrument and we will continue to work with them to collect data at sites of interest.

Sharing Your Work with the Reserves and NOAA

This ACE Basin NERR project has applicability to many of the other coastal Reserves. We are submitting an abstract to present a poster at the 2015 NERR annual meeting to share the findings of the study with the Reserve system. We collaborated with a NOAA scientist, Anne Blair, who we hope will also provide avenues to share the information with other NOAA offices.

Anything Else?

We have been very fortunate to conduct this work with NERR Science Collaborative funding. It allowed us to provide Beaufort County with a more robust scientific dataset to use in their management decisions.

We shared the study findings through the following oral or poster presentations.

Sanger, D., J. Leffler, E. Montie, A. Blair, A. Turner, J. Brunson, G. Riekerk, and K. Pitts. Determining Volume Sensitive Waters in Beaufort County, SC Tidal Creeks. Presented at the Southeastern Estuarine Research Society annual meeting, February 13-15, 2014, Savannah, GA.

Pitts, K., D. Sanger, J. Leffler, J. Brunson, G. Riekerk, R. O'Quinn IV, E. Montie, A. Blair, and A. Turner. Determining Volume Sensitive Waters in Beaufort County, SC Tidal Creeks. Presented at the First Annual Marine Resources Division Conference, March 25-26, 2014, Charleston, SC.

Pirhalla, D., A. Blair, C. Currin, K. Holderied, E. Turner, D. Kidwell. "Impacts of Climate-related Threshold Events - Current NCCOS Research". Presented at the Climate Thresholds Workshop at Hollings Marine Laboratory August 18, 2014, Charleston, SC.

Sanger, D., J. Leffler, A. Blair, A. Tweel, and E. Montie, "Prioritizing Volume Sensitive Tidal Creek Watersheds in Beaufort County, SC". Presentation at 9th Annual Southeast Regional Stormwater Conference, October 8-10, 2014, Charleston, SC.

Tweel, A., D. Sanger, J. Leffler, E. Montie, and A. Blair, "Volume Sensitive Waters in Tidal Creeks of Beaufort County, SC". Presentation at the South Carolina Water Resources Conference, October 15-16, 2014, Columbia, SC.

Tweel, A., D. Sanger, A. Blair, and J. Leffler. "Determining Volume Sensitive Waters in Beaufort County, SC Tidal Creeks". Poster at the National Estuarine Research Reserve System Annual Meeting, November 17-21, 2014, Shepherdstown, WV.

Tweel, A., D. Sanger, A. Blair, and J. Leffler. "Determining Volume Sensitive Waters in Beaufort County, SC Tidal Creeks". Presentation at the Fifth Interagency Conference on Research in the Watersheds, March 2-5, 2015, Charleston, SC.

Tweel, A. "Determining Volume-sensitive Waters in Beaufort County Tidal Creeks". Presented at the Marine Resources Division Conference, March 18-19, 2015, Charleston, SC. Technical audience. 100 attendees.

Blair, A., D. Sanger, and S. Lovelace. "Stormwater Runoff in Watersheds: A System for Predicting Impacts of Development and Climate Change". Presentation at the Fifth Interagency Conference on Research in the Watersheds, March 2-5, 2015, Charleston, SC.

Leffler, J. "Determining Volume Sensitive Waters in Beaufort County, SC Tidal Creeks". Poster at the Fort Johnson Poster Session for Senator Sheldon Whitehouse, April 22, 2014, Charleston, SC.

References

Ahern, D., R. Wagner, and R. Klink 2012. Integrating Stormwater Runoff Quantity and Quality Requirements. North American Surface Water Quality Conference and Exposition. Aug 18-22, 2012. Denver, CO.

Barber, B.P. 2008. Town of Bluffton May River watershed monitoring program. Prepared for Town of Bluffton, Bluffton, SC. 143pp.

Beaufort County (2007). Beaufort County Comprehensive Plan. http://www.bcgov.net/ Council/NewCouncilWeb/ComprehensivePlan/compPlan.php

Blair, A., S. Lovelace, D. Sanger, A.F. Holland, L. Vandiver, and S. White. 2014a. Exploring Impacts of Development and Climate Change on Stormwater Runoff. Hydrological Processes 28(5): 2844-2854.

Blair, A., D. Sanger, D. White, A.F. Holland, L. Vandiver, C. Bowker, and S. White. 2014b. Quantifying and Simulating Stormwater Runoff in Watersheds. Hydrological Processes 28(3): 559-569.

Gutowski W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, and F.W. Zwiers. 2008. Causes of observed changes in extremes and projections of future changes in weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. Karl T.R., G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Holland, A.F., D.M. Sanger, C.P. Gawle, S.B. Lerberg, M. Sexto Santiago, G.H.M. Riekerk, L.E. Zimmerman, and G.I. Scott. 2004. Linkages between tidal creek ecosystems and the landscape and demographic attributes of their watersheds. Journal of Experimental Marine Biology and Ecology 298:151-178.

Island Packet. 2001. Report shows importance of controlling stormwater. The Island Packet, August 15, 2001.

Karl, T.R., J.M. Melillo, and T.C. Peterson (eds.) 2009. Global Climate Change Impacts in the United States. Cambridge University Press, New York, NY. 189 pp.

Maier, P. (ed.) 2010. Ashepoo-Combahee-Edisto (ACE) Basin National Estuarine Research Reserve Management Plan 2011-2016. South Carolina Department of Natural Resources, Charleston, SC. 142 pp.

Melillo, J.M., T.C. Richmond, and G.W. Yohe (eds.) 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Pollack, J.A. and R.W. Walker Szivak. 2007. Training Needs Assessment of Professional Decision Makers in the Coastal Counties of South Carolina. North Inlet-Winyah Bay and ACE Basin National Estuarine Research Reserve Coastal Training Programs, February 2007. 24 pp.

Sanger D., A. Blair, G. DiDonato, T. Washburn, S. Jones, G. Riekerk, E. Wirth, J. Stewart, D. White, L. Vandiver, and A.F. Holland. 2015. Impacts of Coastal Development on the Ecology and Human Well-being of Tidal Creek Ecosystems of the US Southeast. Estuaries and Coasts 38:S49-S66.

Schueler T. 1994. The importance of imperviousness. Watershed Protection Techniques 1(3): 100–111.

Small, T.D., M.R. Ide, and J.M. Keesee. 2010. CDMO NERR SWMP Data Management Manual, Version 6.3. NOAA National Estuarine Research Reserve Centralized Data Management Office, Georgetown, SC. 244 pp.

Town of Bluffton. 2008. Water Body Management Plan for the May River. http://www.townofbluffton.com/epa/waterbodyplan6.16.08.pdf

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2004. National Engineering Handbook, Part 630, Chapter 10, Estimation of direct runoff from storm rainfall.

Van Dolah, R.F., D.E. Chestnut, and G.I. Scott. 2000. A Baseline Assessment of Environmental and Biological Conditions in Broad Creek and the Okatee River, Beaufort County, South Carolina. Final Report. Submitted to Beaufort County Council, Beaufort, SC. 280pp

Walker, R. (ed.) 2010. Ashepoo-Combahee-Edisto (ACE) Basin National Estuarine Research Reserve Coastal Training Program Strategic Plan. South Carolina Department of Natural Resources, Charleston, SC.

Appendix A. Figures and Tables

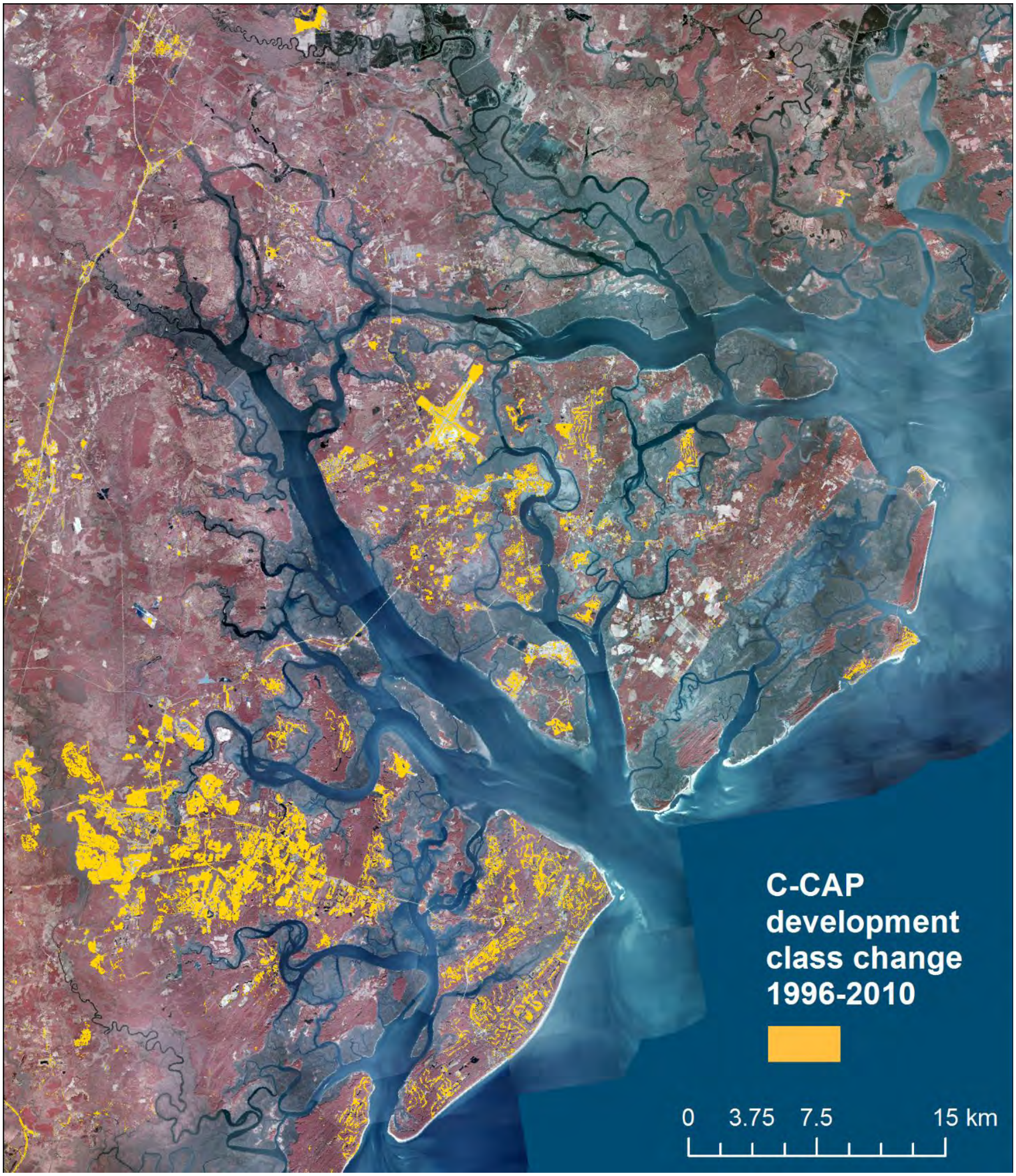


Figure 1. NOAA Coastal Change Analysis Program (C-CAP) change analysis for 1996 to 2010 in the Beaufort County area. Areas shown in yellow changed land use category from undeveloped to developed, or from a less developed category to a more developed category. Base layer is SCDNR NAPP IR 2010 image.

Figure 2. Watershed boundaries used in watershed study (yellow lines), based on USGS HUC-12 boundaries. Headwater portions of the largest watersheds were also analyzed separately (dashed lines). Base layer is USDA NAIP 2013 image.

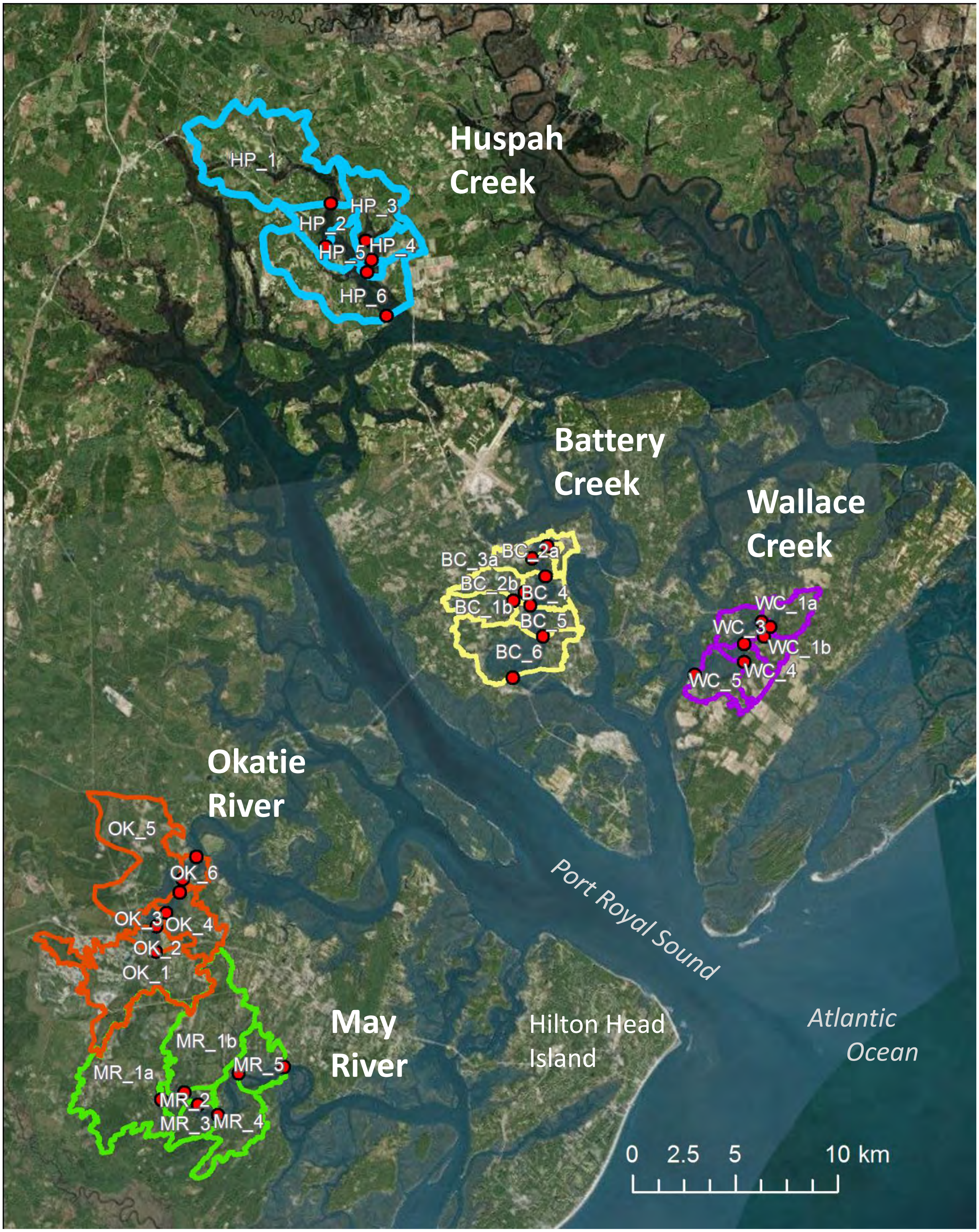


Figure 3. Aerial map of Beaufort County depicting study watersheds for Okatie River (orange), May River (green), Battery Creek (yellow), Wallace Creek (purple), and Huspah Creek (blue). Labels indicate subwatersheds and datalogger locations. WC is Wallace Creek, BC is Battery Creek, OK is Okatie River, MR is May River, HP is Huspah Creek. Base layer is USDA NAIP 2013 image.

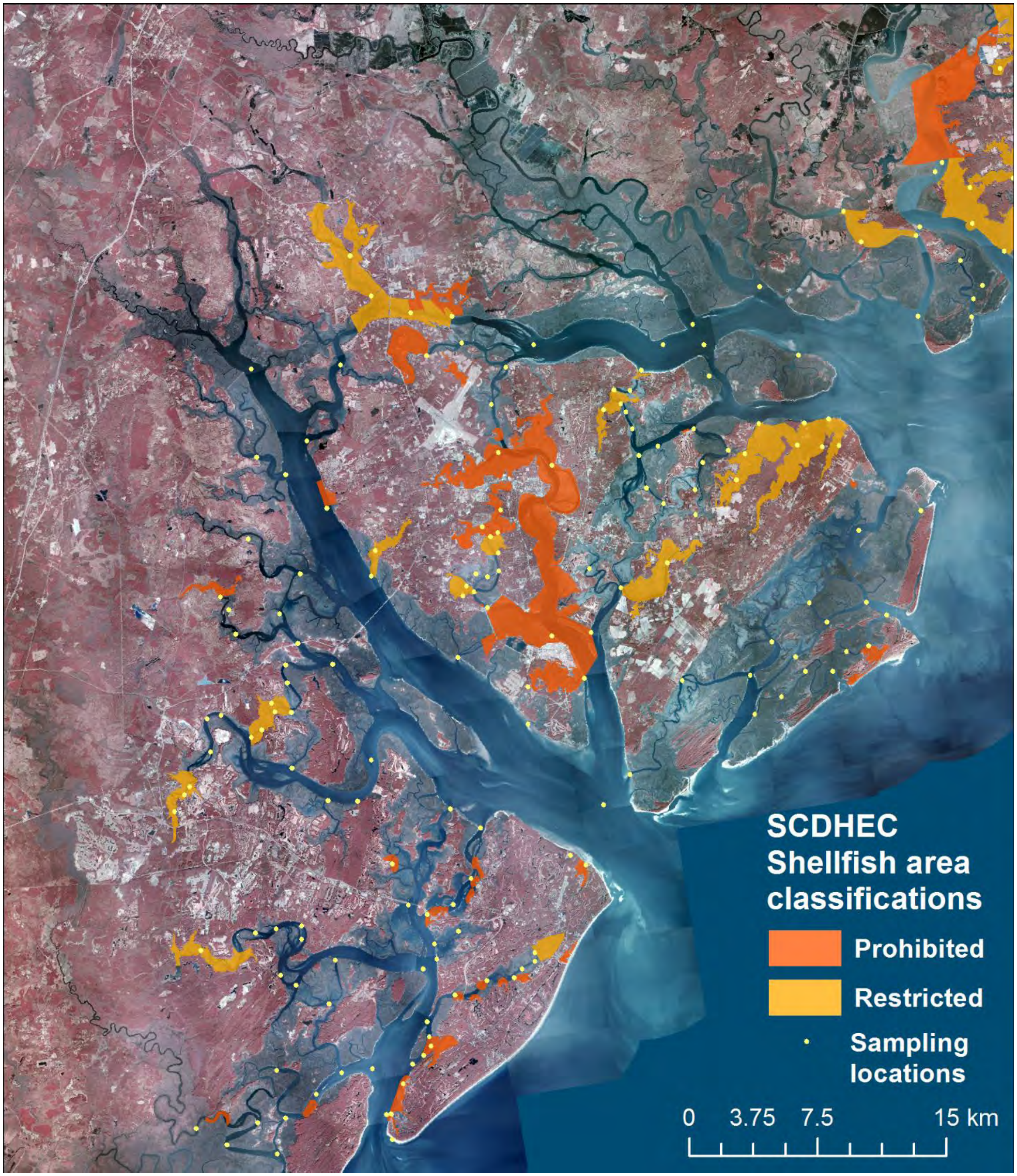


Figure 4. South Carolina Department of Health and Environmental Control (SCDHEC) shellfish zone classifications and water quality sampling locations. Headwater portions of tidal creeks are often classified as restricted or prohibited. Base layer is SCDNR NAPP IR 2010 image.

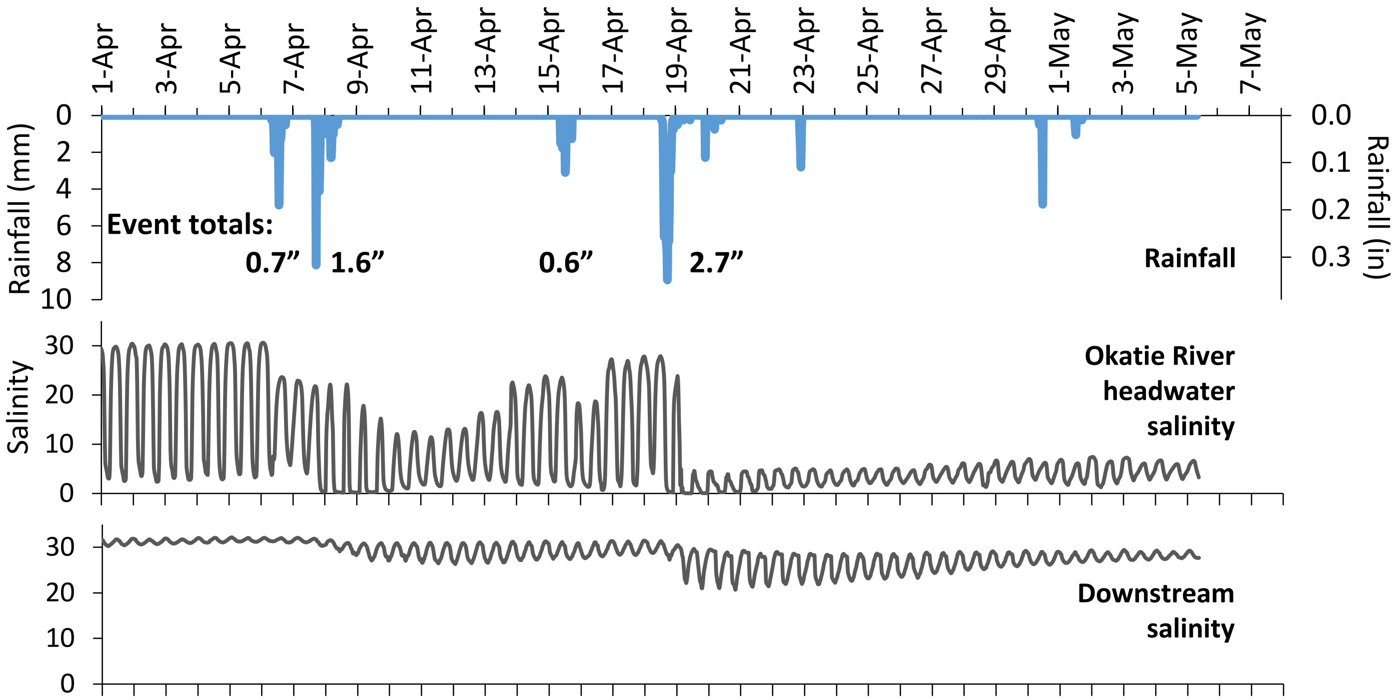


Figure 5. Example data collected from the Okatie River from April 1 to May 8, 2014. Salinity varies over the course of the two tidal cycles per day and ranges were much greater and much more influenced by rain events in the tidal creek headwaters (OK1) compared to farther downstream (OK6).

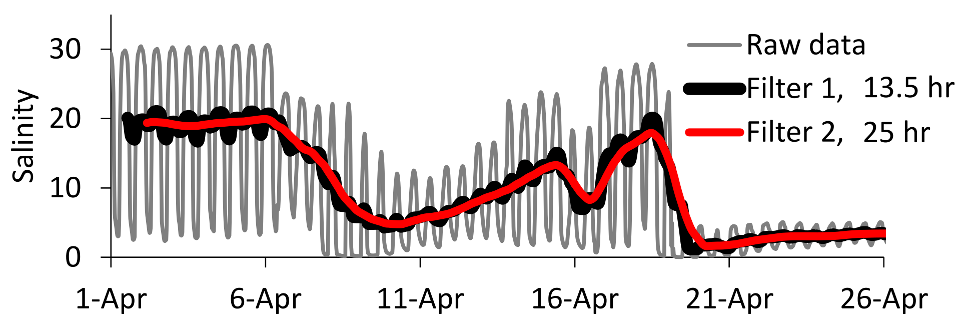


Figure 6. An example of salinity data filtered to isolate stormwater impacts from tidal effects.

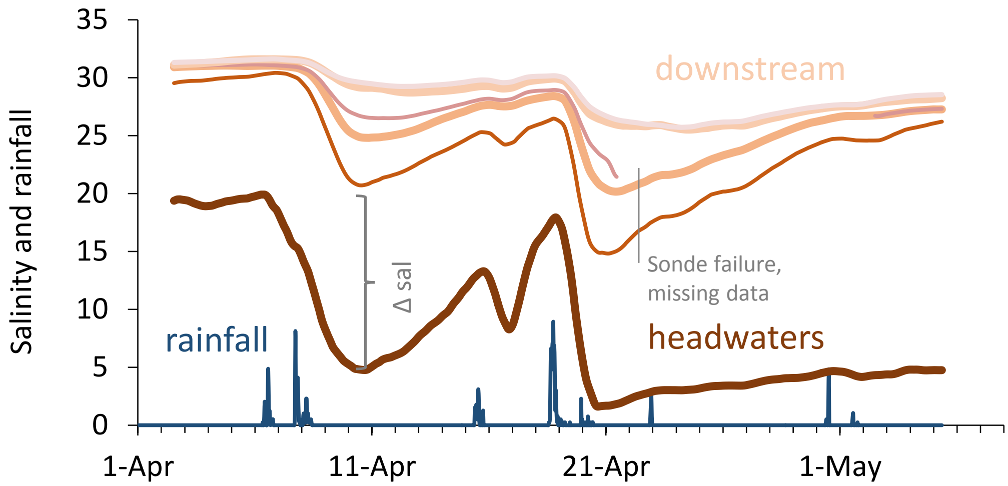


Figure 7. An example of filtered salinity data for all six Okatie River sites from two primary rain events in spring 2014. Darker colors represent more headwater sites, salinity response is dampened as the freshwater signal progresses downstream. An example of a salinity drop is brackted as Δ sal for the first rain event.

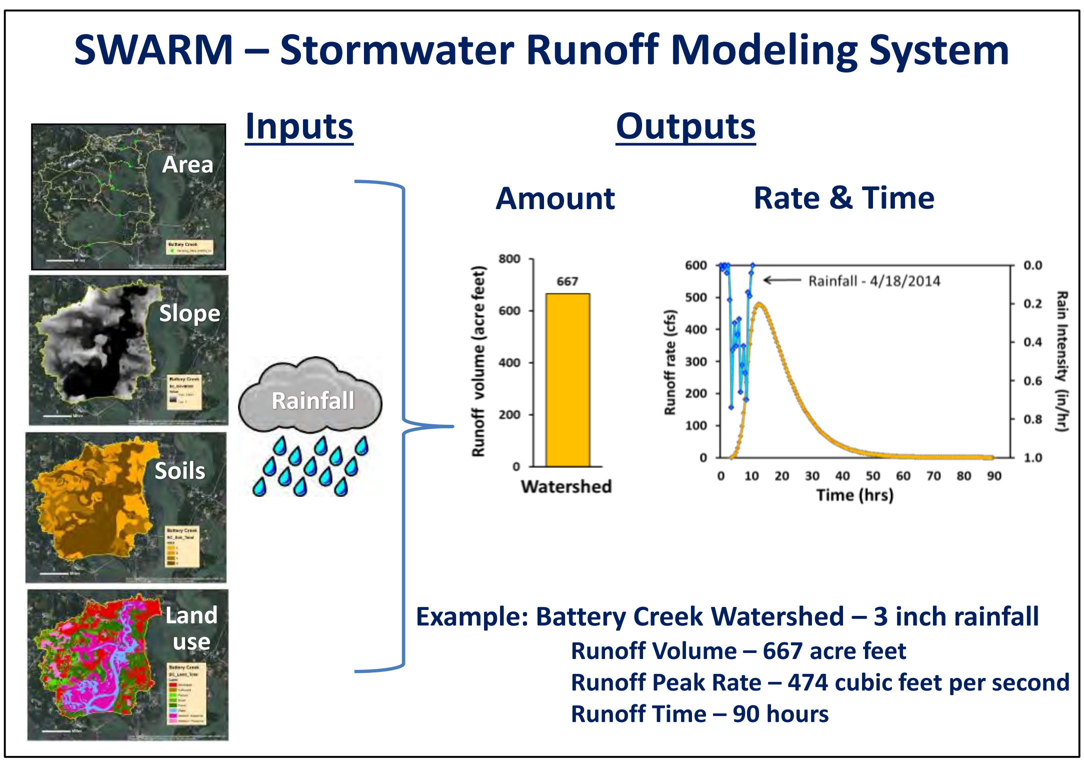


Figure 8. Diagram of general elements of SWARM. Model inputs are shown on the left. Model outputs are shown in the center and right. Specific input and output data are provided at the lower right.

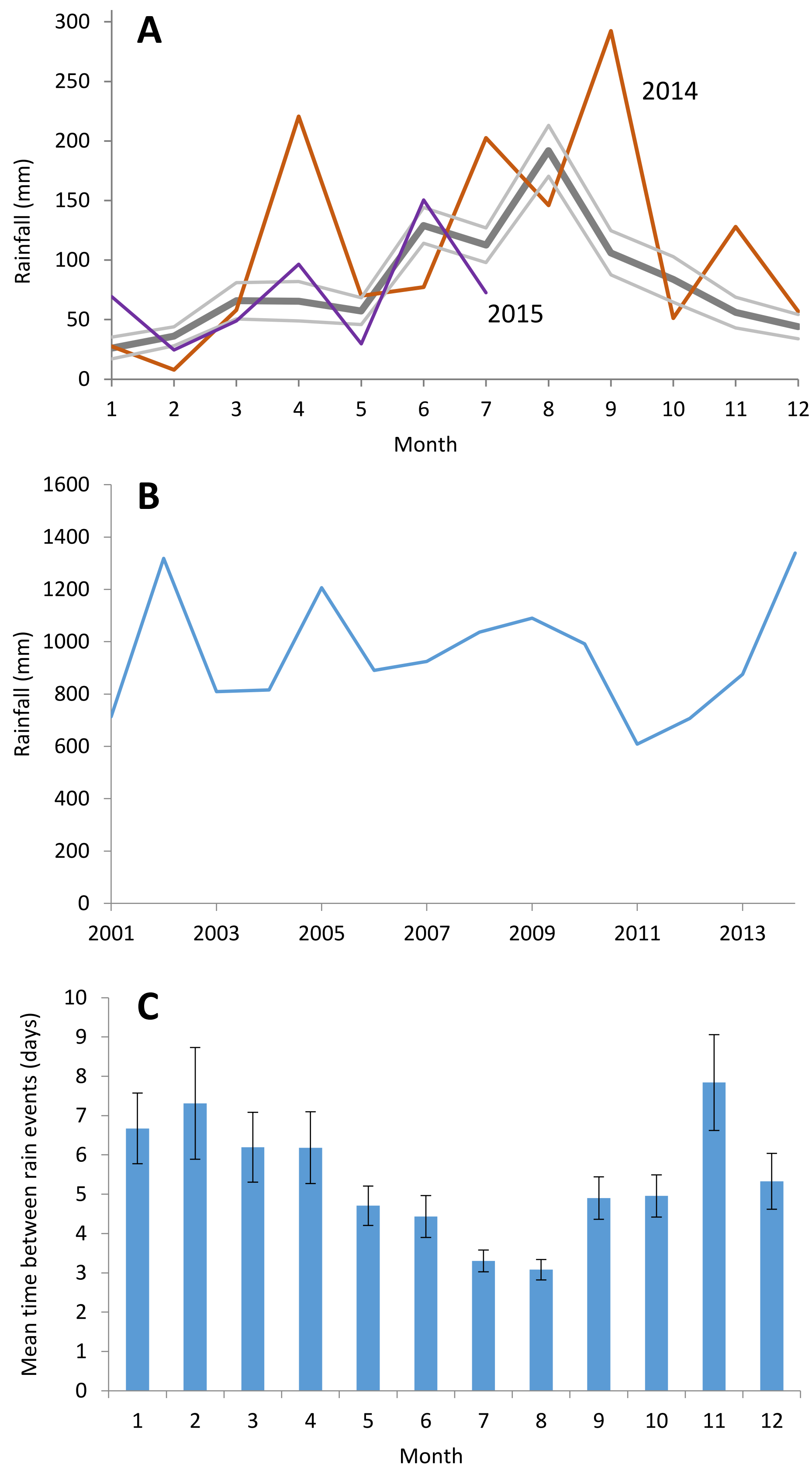


Figure 9. Summary of ACE Basin NERR meteorological data collected at Bennett's Point, South Carolina. **(A)** Mean monthly precipitation (± 1 S.E.) 2001-2014, overlain with study years 2014 and 2015. **(B)** Annual rainfall totals. **(C)** Average number of days (± 1 S.E.) between rain events for all years, by month.

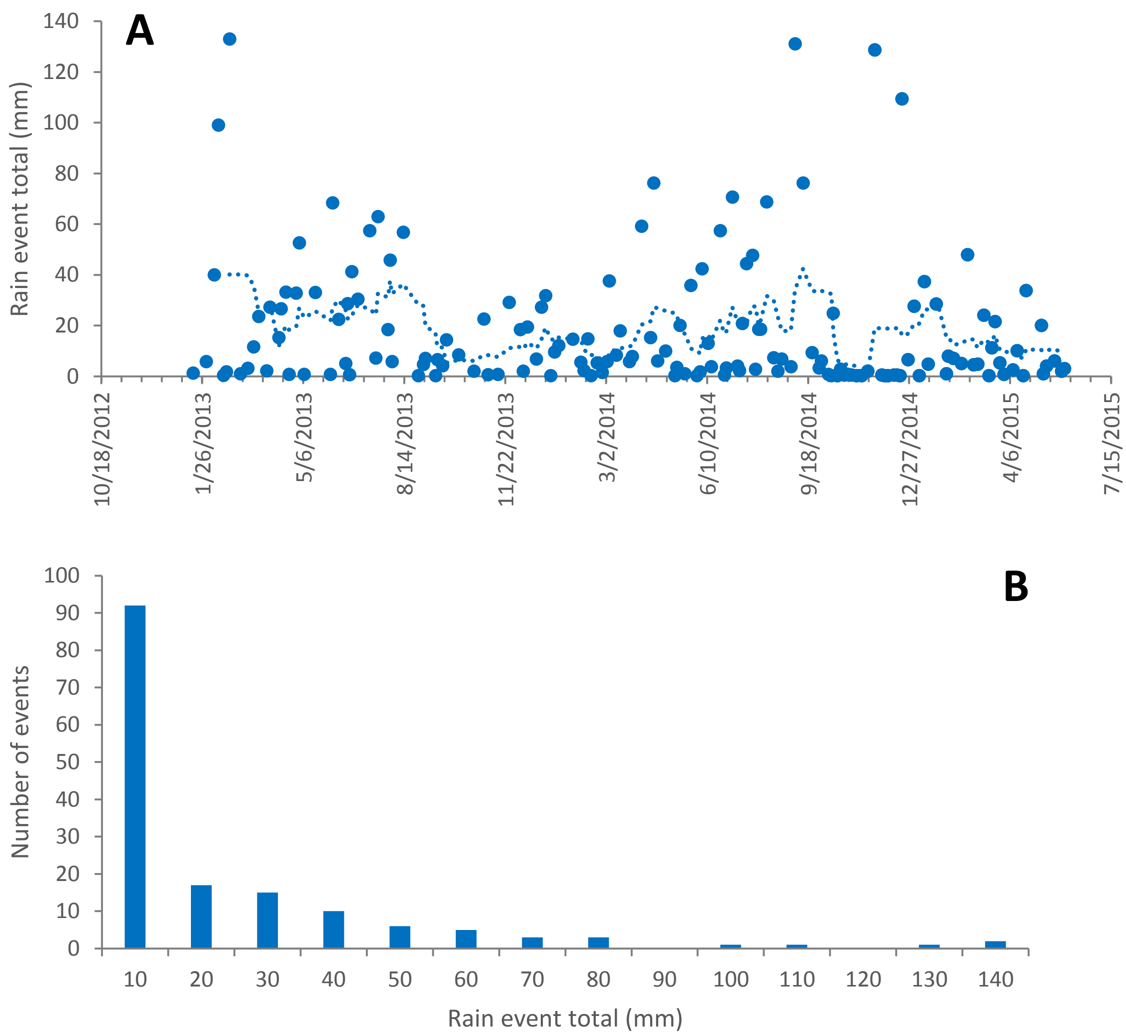


Figure 10. Summary of meteorological data collected for this study. Only data for Okatie River gauge is shown, other sites exhibit similar patterns. **(A)** Rain event totals over the course of the study, and the moving average shows periods of higher and lower rainfall. **(B)** Histogram of rain event totals by 10 mm bin.

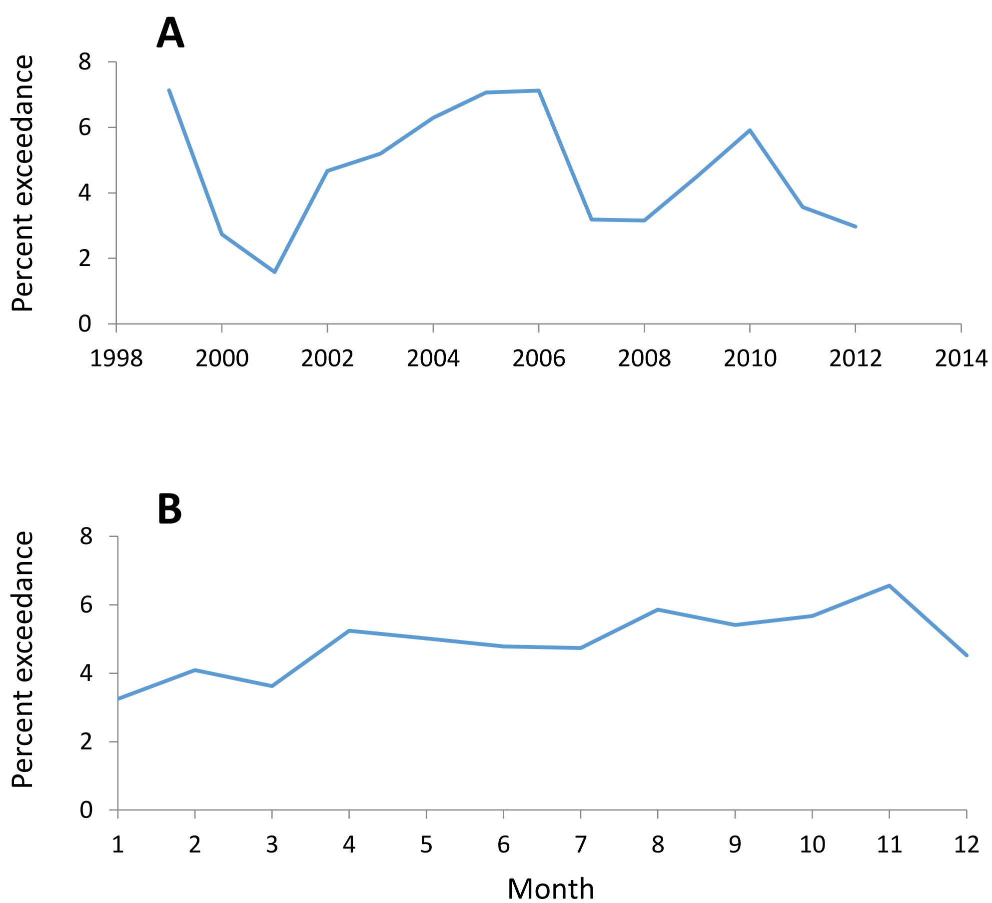


Figure 11. Summaries of SCDHEC fecal coliform water quality sample results by year **(A)** and month **(B)** for all available sample data collected in Beaufort County, South Carolina. Exceedance criteria is defined as greater than 40.9 cells/100 ml.

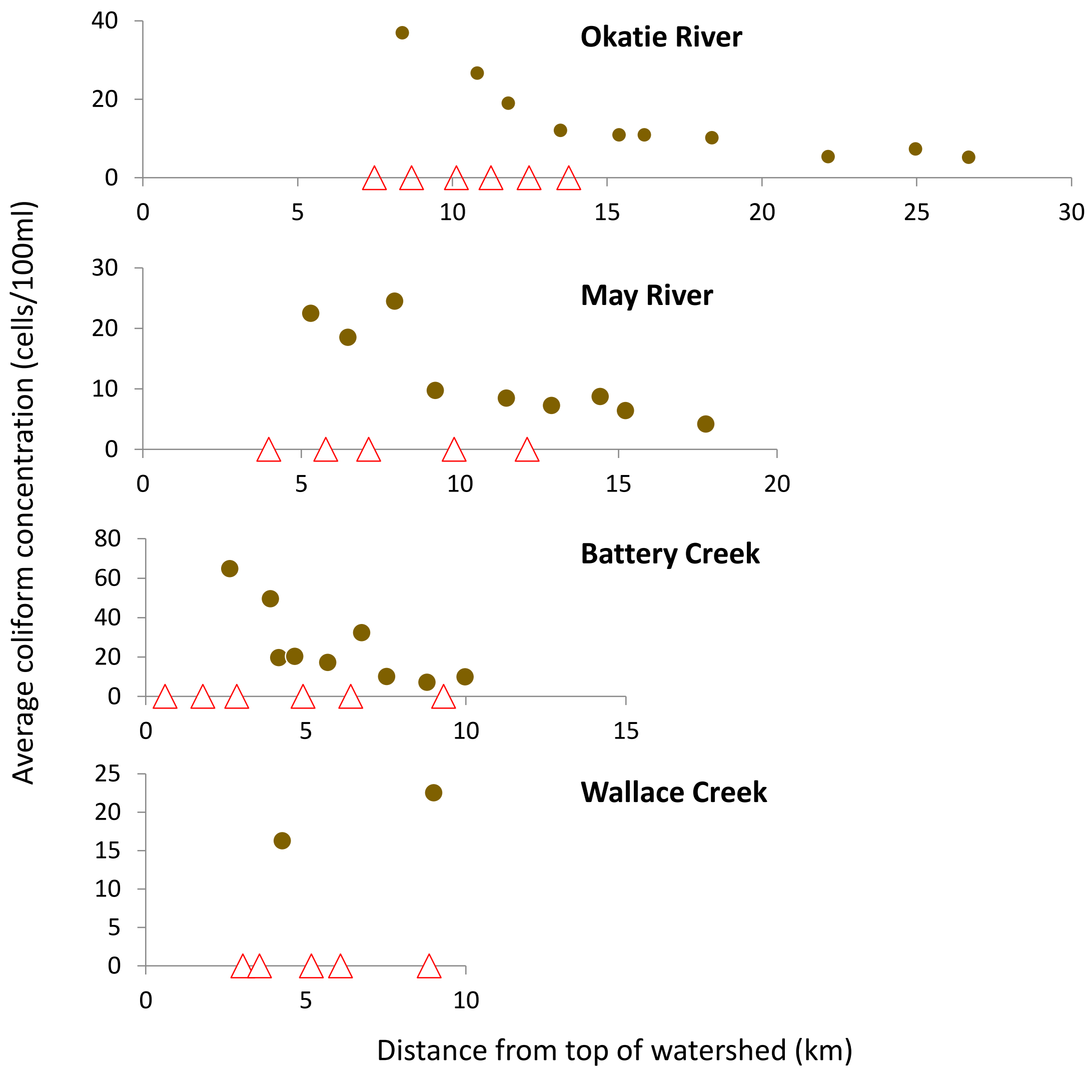
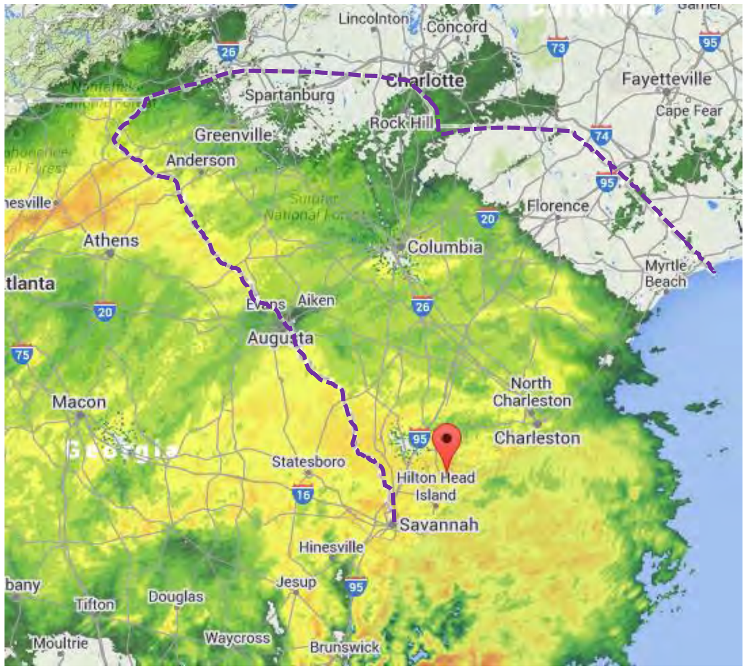


Figure 12. Summaries of SCDHEC fecal coliform water quality sample results by location within the study systems (brown) for all available data. Our study sites down the length of each creek are shown as red triangles. Note differing y-axis scales.



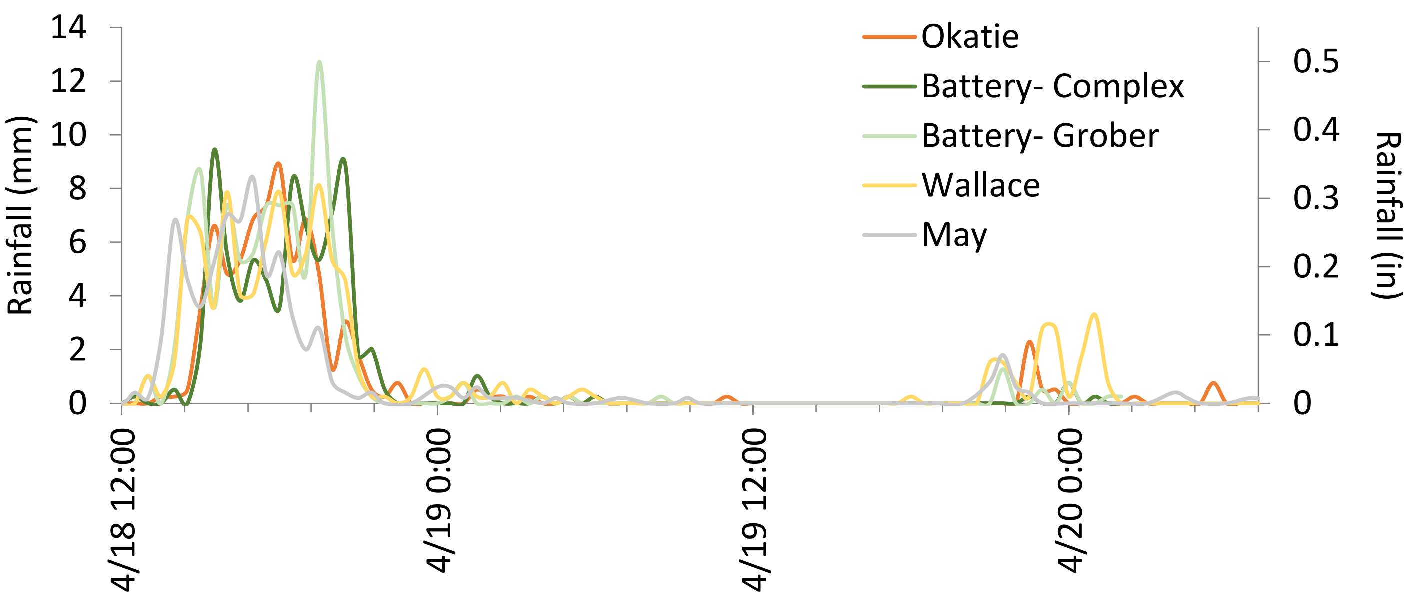


Figure 13. An example of a large rain event on April 18, 2014, showing similarities and differences between the five study rain gauges. This large rain event yielded similar rain totals and timing for all study watersheds, and was used as a case study to learn about salinity response in greater detail.

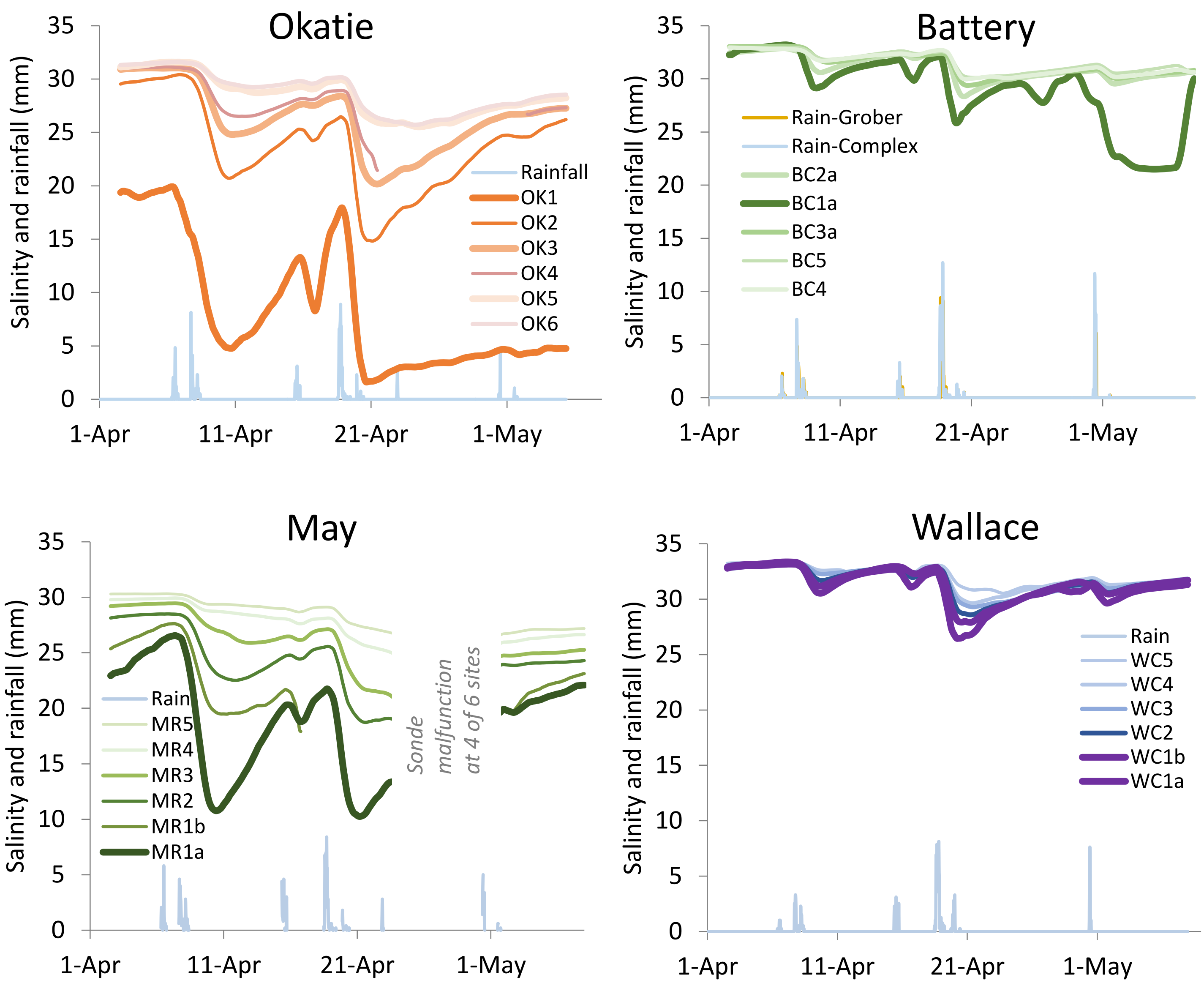


Figure 14. Examples of filtered salinity data for the four main study watersheds from two primary rain events in spring 2014. Darker colors represent more headwater sites, salinity response was dampened as the freshwater signal progressed downstream. The Okatie River and May River watersheds exhibited much larger salinity drops than Battery Creek and Wallace Creek watersheds for the same rain events.

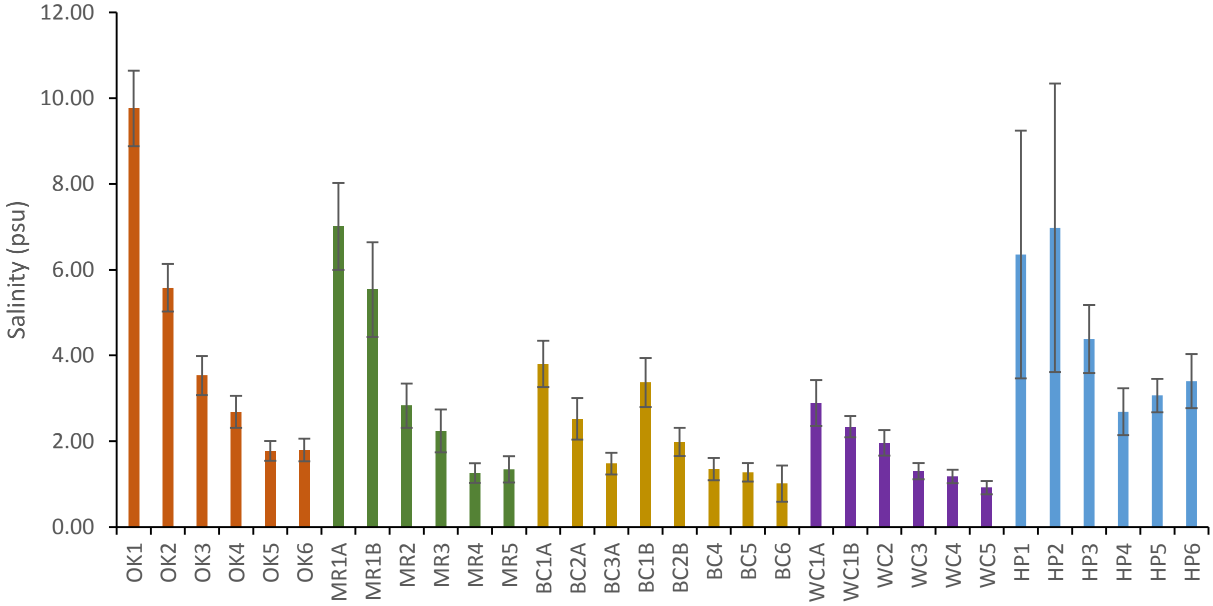


Figure 15. Average salinity drop observed at each site. Error bars represent one standard error. Average was computed across all rain events.

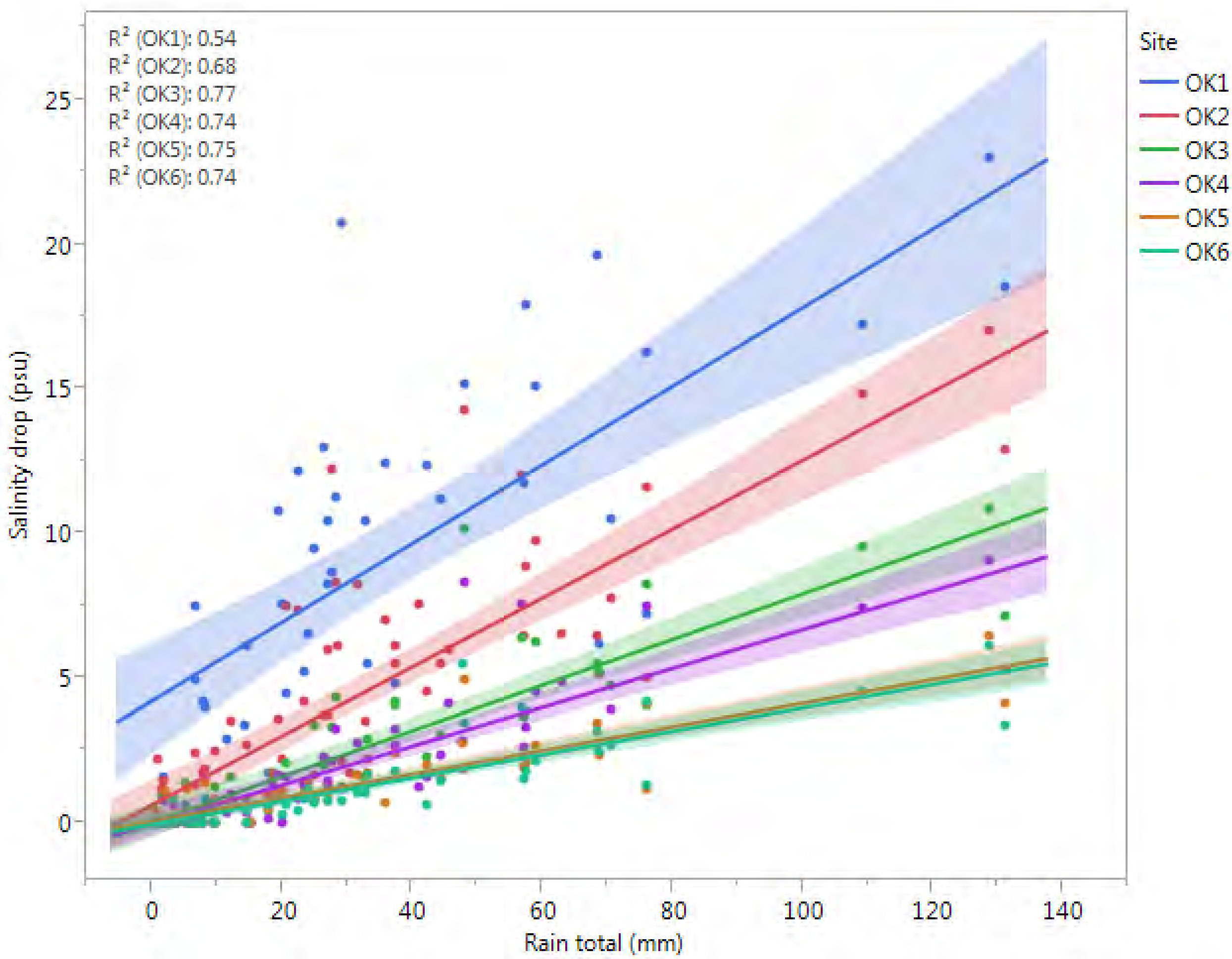


Figure 16. Relationship between rainfall total and salinity drop for the study sites in the Okatie River. The R^2 is provided for each site.

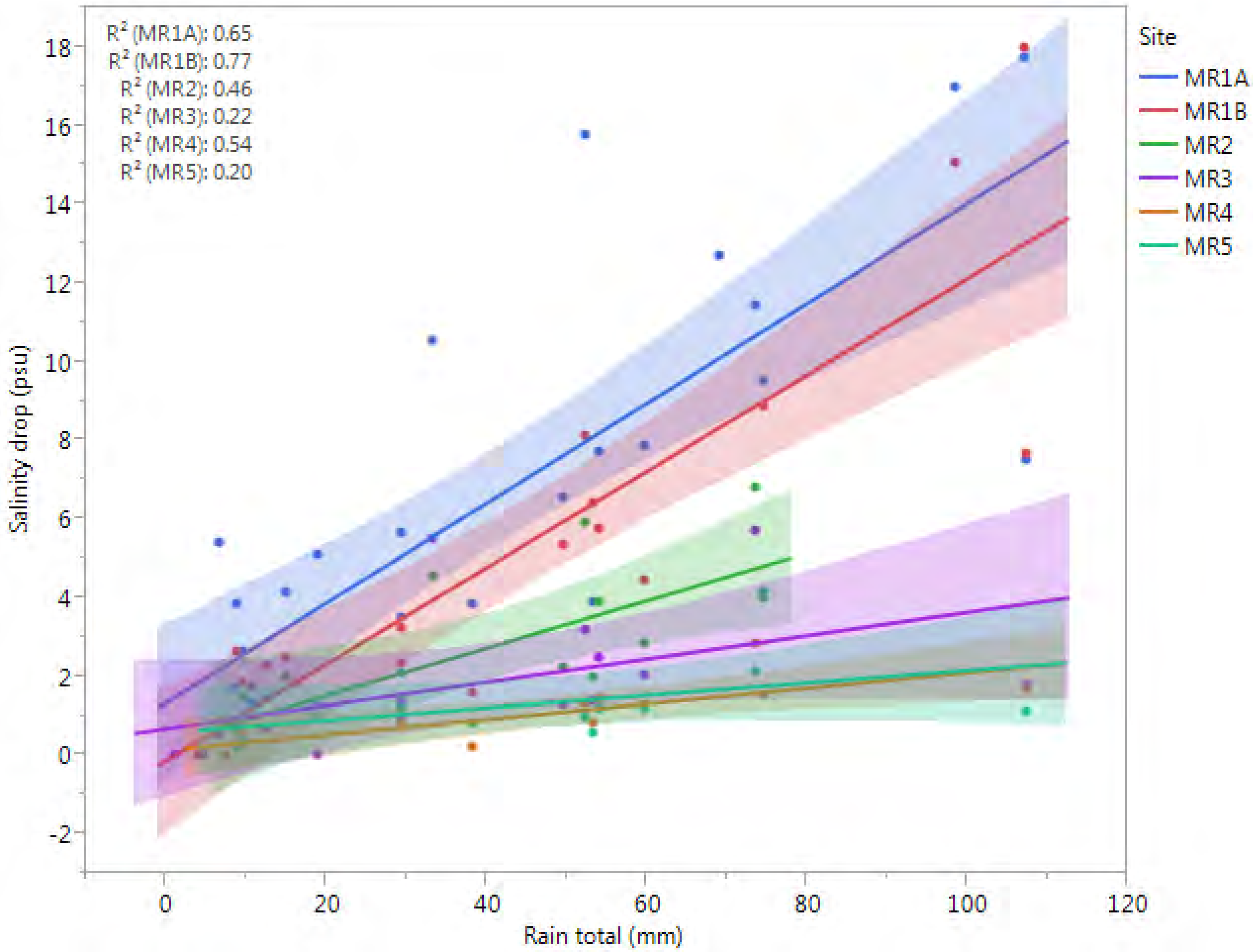


Figure 17. Relationship between rainfall total and salinity drop for the study sites in the May River. The R^2 is provided for each site.

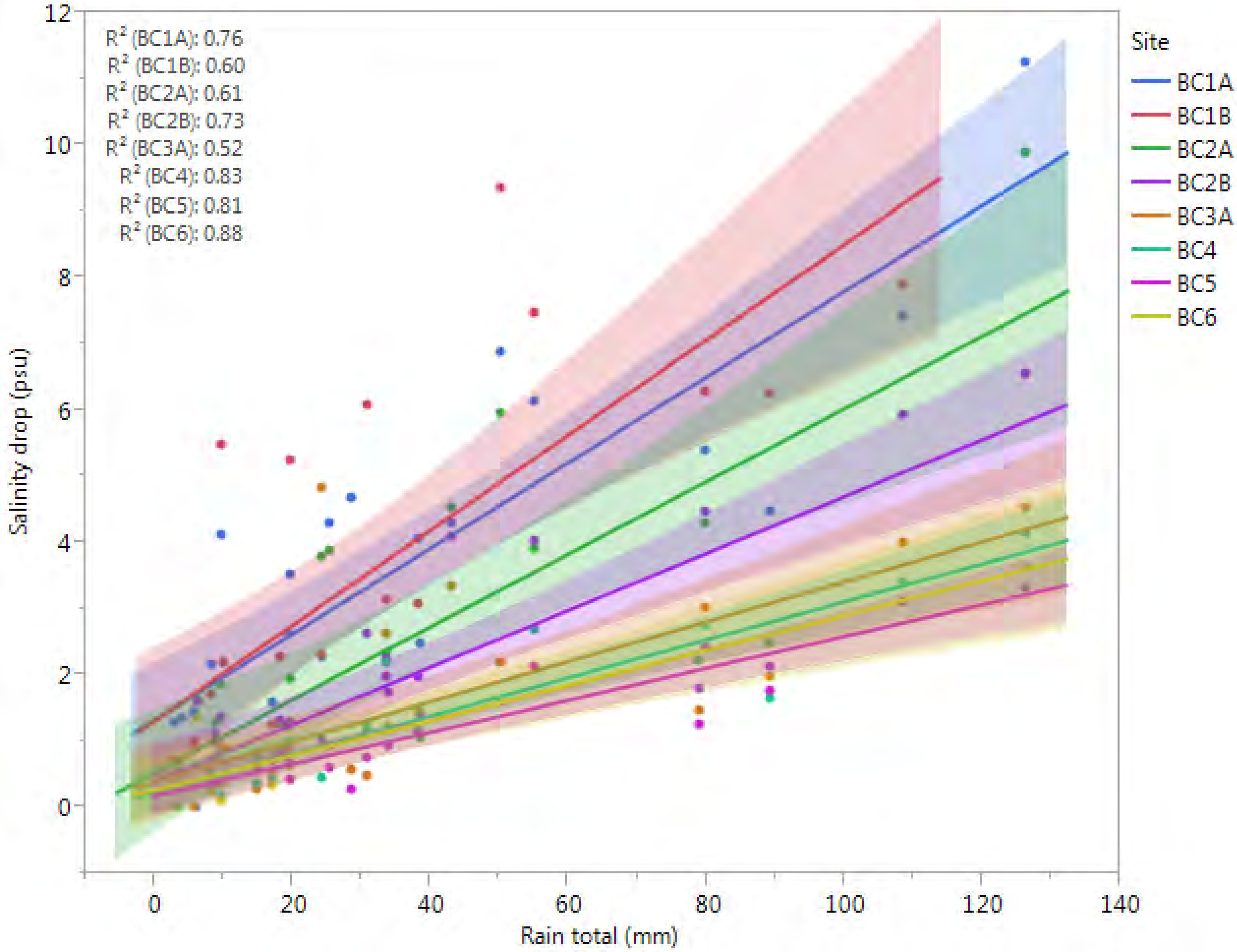


Figure 18. Relationship between rainfall total and salinity drop for the study sites in Battery Creek. The R^2 is provided for each site.

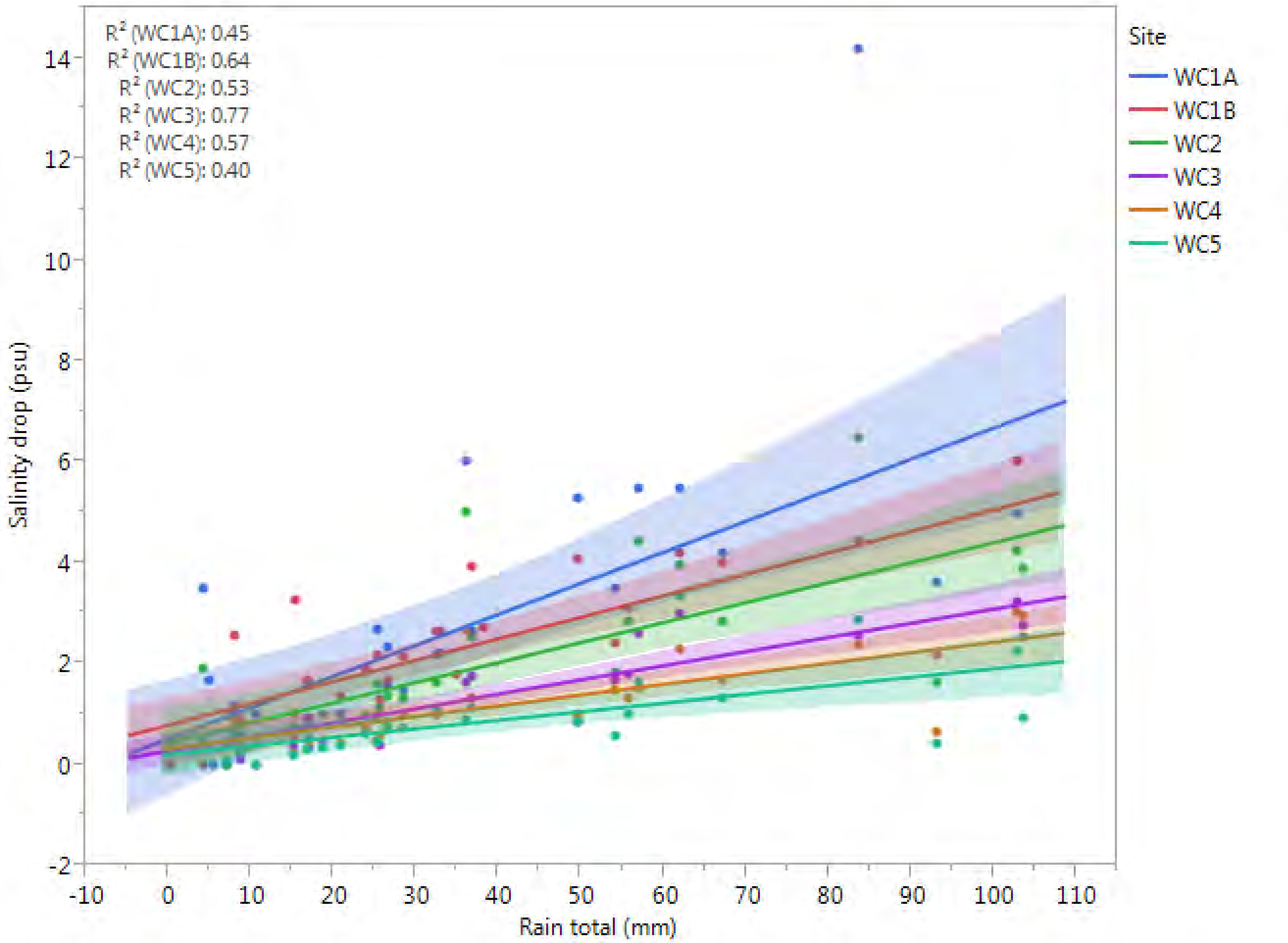


Figure 19. Relationship between rainfall total and salinity drop for the study sites in Wallace Creek. The R^2 is provided for each site.

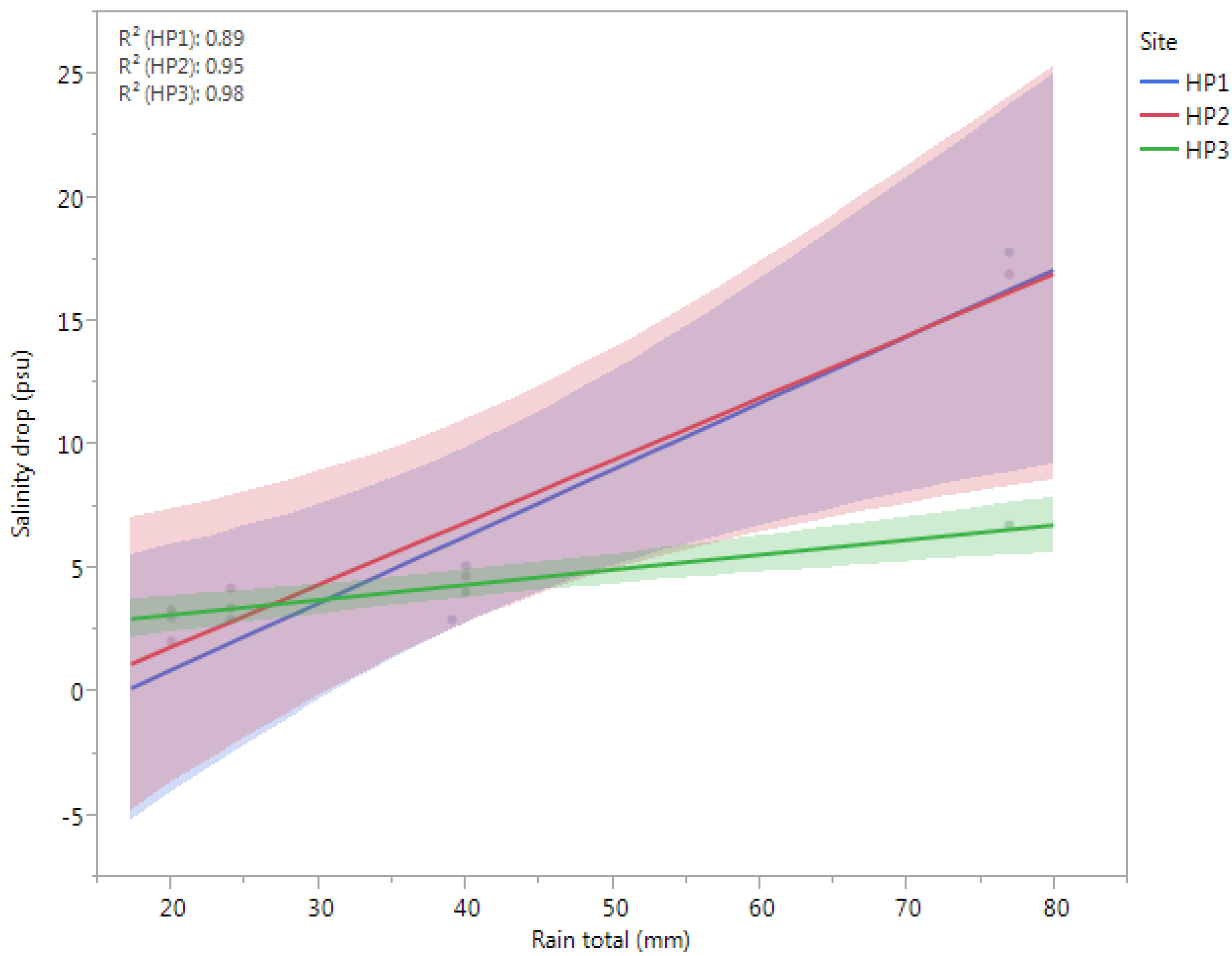


Figure 20. Relationship between rainfall total and salinity drop for the study sites in Huspah Creek. The R^2 is provided for each site. Sites HP4, HP5, and HP6 are not shown due to high p values ($p > 0.2$).

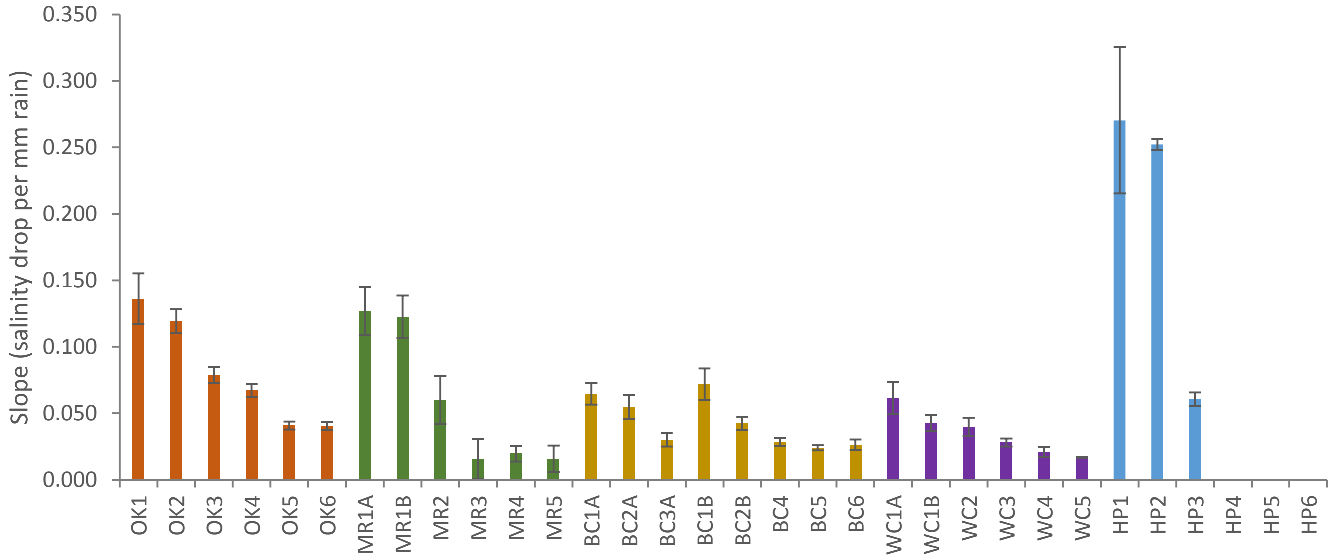


Figure 21. Slopes of equations for regressions of rain total (x) vs salinity drop (y). Huspah 4, 5, and 6 were not significant and are not shown ($p > 0.2$). All other regressions were significant except for May River 3 and 5 ($p < 0.05$).

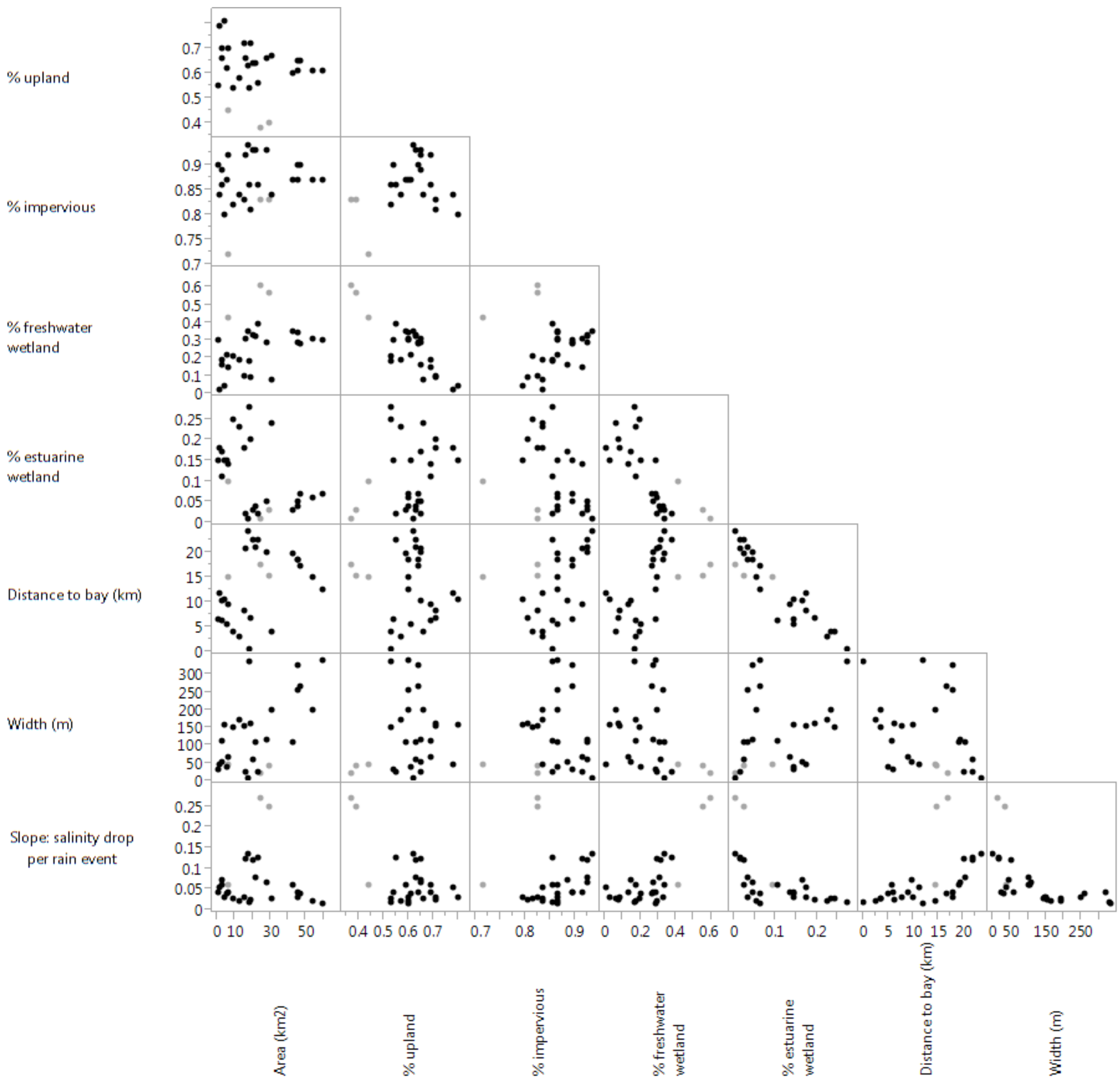


Figure 22. Scatterplot matrix of select variables used in the multivariate analysis. Huspah Creek headwater sites (HP1, HP2, HP3) appear in grey and were included in the analysis. The downstream sites exhibited no significant relationship, likely due to sparse data (max n=5 for Huspah). Variables suggesting curvilinear relationships (e.g., % saltwater wetland) were tested as such in the regression analysis.

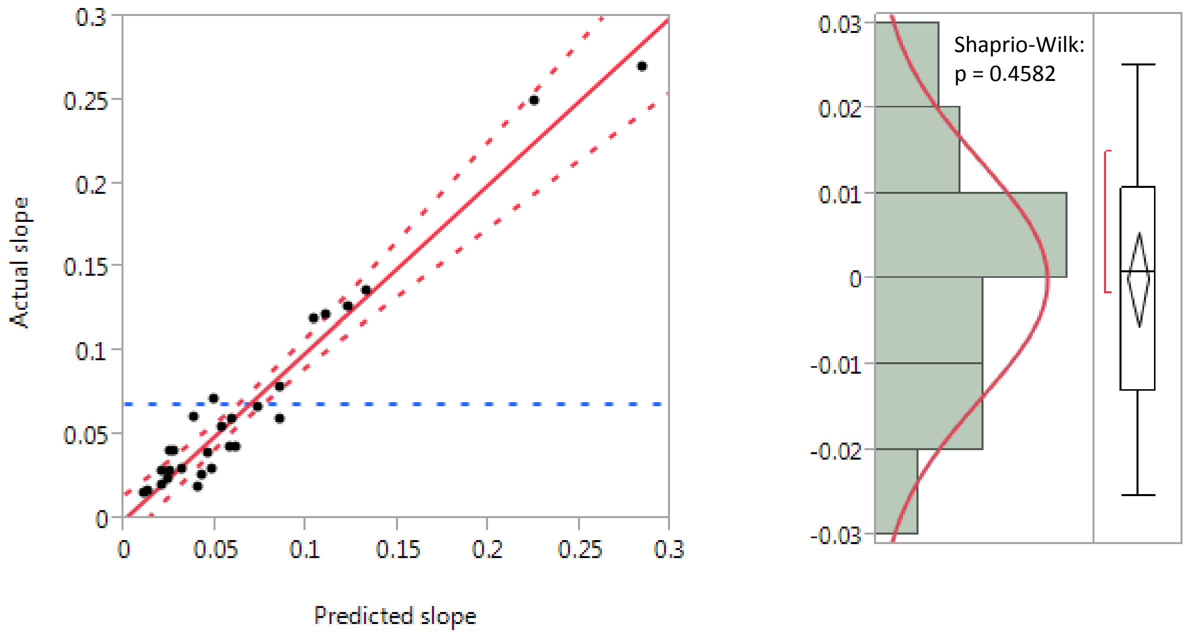


Figure 23. Model performance and normality test of residuals for best regression model to predict slope (salinity drop per mm rainfall) in study subwatersheds for each site.

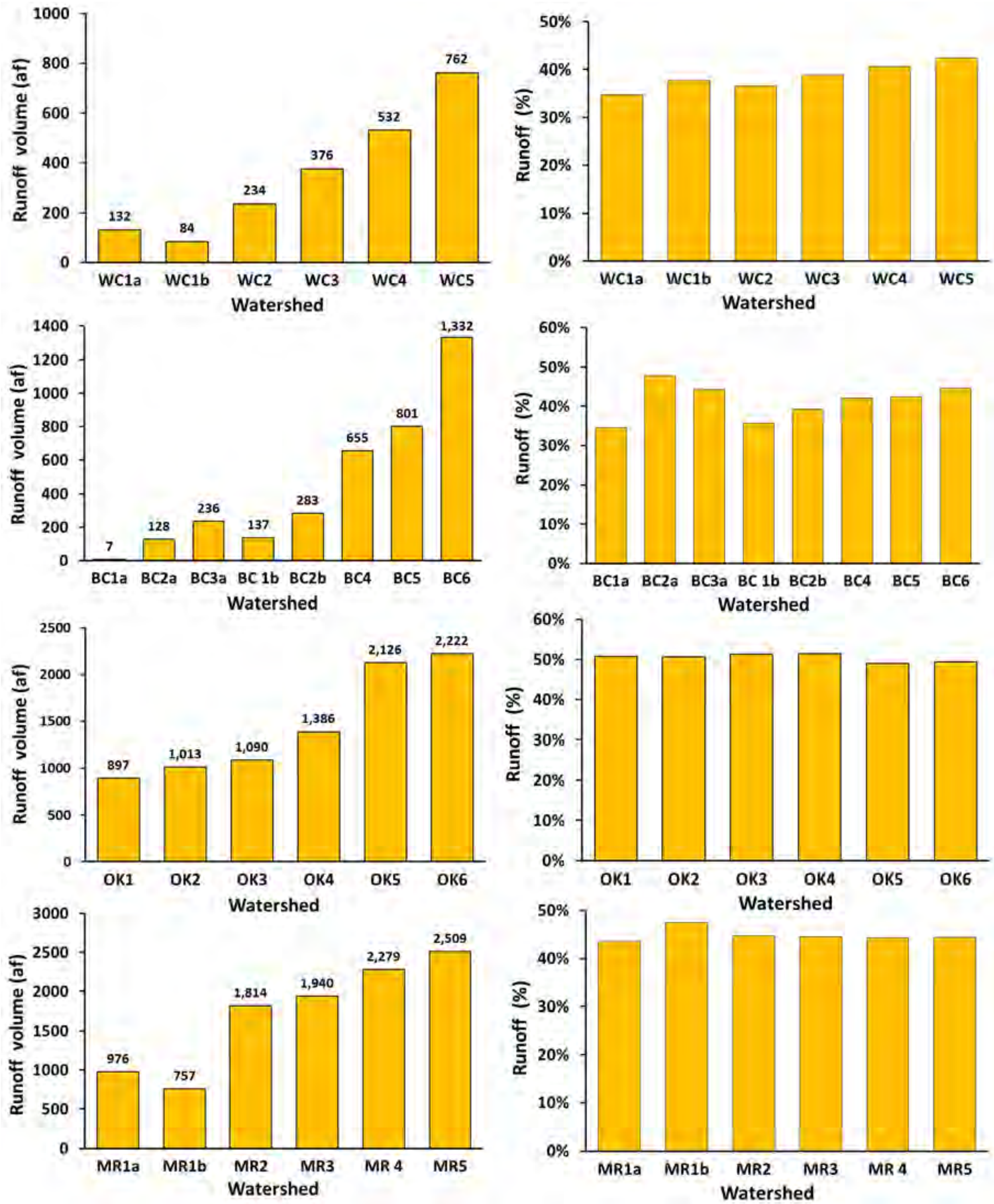


Figure 24. Runoff modeled using a 4.5 inch rain event for each of the 4 primary creek systems. Charts on the left side show output in actual volume (af is acre feet). Charts on the right side show output as a percentage of the rainfall that was converted to runoff (which removes the variance caused by area differences).

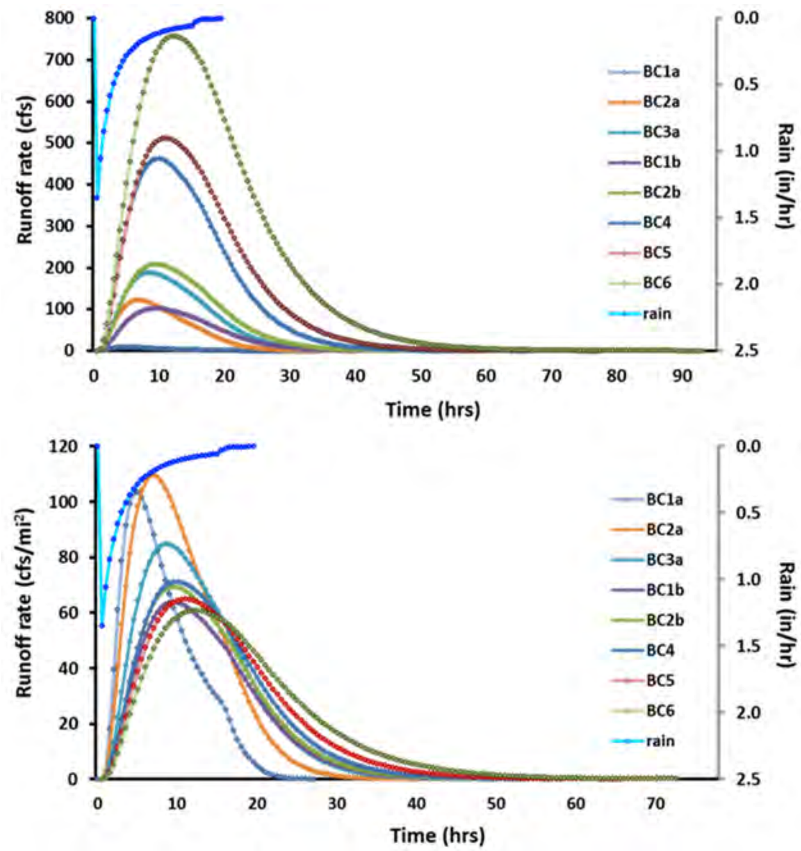


Figure 25. Hydrographs for a design 4.5 inch 24-hour rain event in each Battery Creek watershed for each site. The x-axis shows runoff time, the primary y axis shows runoff rate, and the secondary y-axis rain intensity in inches per hour. The upper chart shows the actual modeled rate in cubic feet per second (cfs). The lower chart shows a normalized rate of cfs per watershed square mile in order to remove the effect of different watershed areas. The space under each curve represents the volume of runoff.

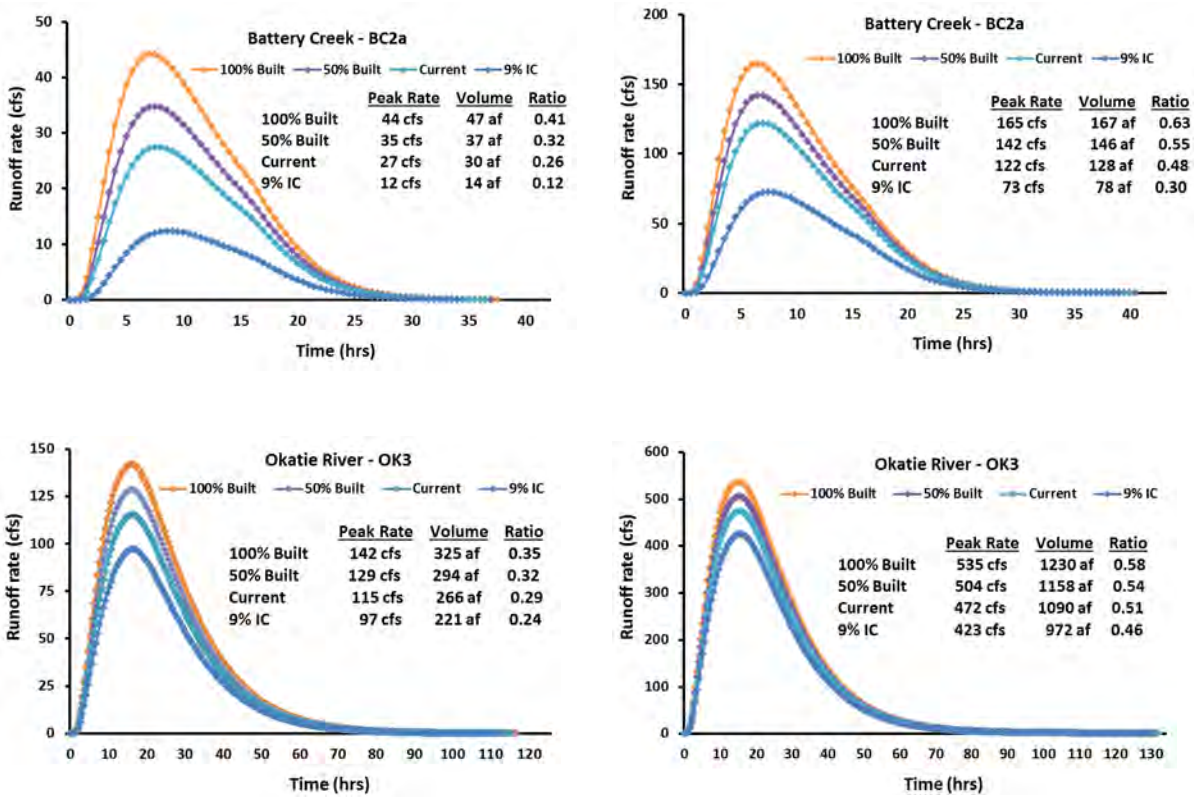


Figure 26. Development scenarios for two of the volume sensitive watersheds: BC2a (top) and OK3 (bottom). The x axis shows runoff time, and the y axis shows runoff rate. The charts on the left are modeled on a 1.95 inch 24-hour rain (95th percentile rain); the charts on the right are based on a 4.5 inch 24-hour rain (2-year storm). 100% Built is projecting additional watershed development for all of dry land not yet developed. 50% Built projects development for 50% of dry land not yet developed. Current is present watershed development. 9% IC is the percent of impervious cover reflecting the threshold of measurable environmental degradation from development. cfs is cubic feet per second, af is acre feet, hrs is hours. Peak rate is the maximum cfs for the modeled runoff. Ratio is proportion of rainfall converted to runoff. The area under each curve represents the volume of runoff.

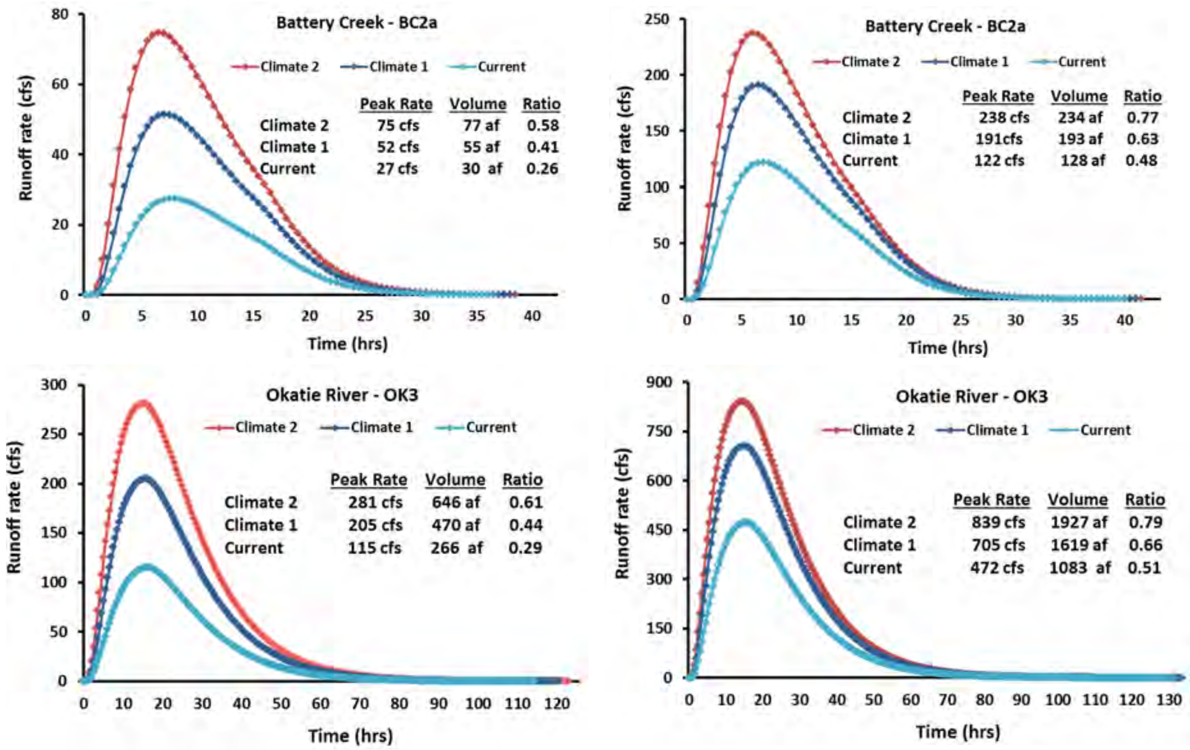


Figure 27. Climate scenarios for two of the volume sensitive watersheds: BC2a (top) and OK3 (bottom). The x axis shows runoff time, and the y axis shows runoff rate. The charts on the left are modeled on a 1.95 inch 24-hour rain (95^{th} percentile rain); the charts on the right are based on a 4.5 inch 24-hour rain (2-year storm). Current scenario uses average antecedent runoff conditions (ARC), Climate 1 scenario uses semi-wet ARC, and Climate 2 scenario uses wet ARC. Both rainfalls are increased by 15% for the climate scenarios. cfs is cubic feet per second, af is acre feet, hrs is hours. Peak rate is the maximum cfs for the modeled runoff. Ratio is proportion of rainfall converted to runoff. The area under each curve represents the volume of runoff.

Table 1. Linear regression equations to predict runoff volume in each watershed at current development levels and with average runoff conditions. Y is runoff (acre feet), and x is rainfall amount (mm). WC is Wallace Creek, BC is Battery Creek, OK is Okatie River, MR is May River.

Watershed	Regression Equation - Volume	r^2
WC1a	$y = 0.0082\ x^2 + .2678\ x - 6.4477$	0.999
WC1b	$y = 0.0049\ x^2 + .2107\ x - 4.4992$	0.999
WC2	$y = 0.014\ x^2 + .5466\ x - 12.144$	0.999
WC3	$y = 0.0215\ x^2 + 1.0054\ x - 20.695$	0.999
WC4	$y = .0293\ x^2 + 1.5625\ x - 30.544$	0.999
WC5	$y = 0.0404\ x^2 + 2.4311\ x - 45.44$	0.999
BC1a	$y = 0.0005\ x^2 + 0.0149\ x - 0.3621$	0.999
BC2a	$y = 0.006\ x^2 + 0.5041\ x - 8.3966$	0.999
BC3a	$y = 0.012\ x^2 + 0.8198\ x - 14.63$	0.999
BC1b	$y = 0.0084\ x^2 + 0.2978\ x - 6.8798$	0.999
BC2b	$y = 0.016\ x^2 + 0.7748\ x - 15.739$	0.999
BC4	$y = 0.0349\ x^2 + 2.0668\ x - 38.851$	0.999
BC5	$y = 0.0425\ x^2 + 2.5546\ x - 47.755$	0.999
BC6	$y = 0.0672\ x^2 + 4.6579\ x - 82.831$	0.999
OK1	$y = 0.0391\ x^2 + 3.8871\ x - 61.48$	0.999
OK2	$y = 0.0443\ x^2 + 4.3728\ x - 69.403$	0.999
OK3	$y = 0.047\ x^2 + 4.797\ x - 75.302$	0.999
OK4	$y = 0.0595\ x^2 + 6.1264\ x - 95.86$	0.999
OK5	$y = 0.0967\ x^2 + 8.7356\ x - 142.38$	0.999
OK6	$y = 0.1003\ x^2 + 9.2319\ x - 149.58$	0.999
MR1a	$y = 0.0504x^2 + 3.2746x - 59.547$	0.999
MR1b	$y = 0.0357x^2 + 2.9555x - 49.536$	0.999
MR2	$y = 0.0911x^2 + 6.3921x - 113.2$	0.999
MR3	$y = 0.0979x^2 + 6.7922x - 120.72$	0.999
MR4	$y = 0.1157x^2 + 7.8925x - 141.11$	0.999
MR5	$y = 0.1268x^2 + 8.752x - 155.86$	0.999

Table 2. Salinity drop summary data and regression results for all subwatersheds monitored. Regressions compared rainfall total (mm) to observed salinity drop. Additional variables were studied, but rainfall total exhibited the greatest correlation to salinity drop.

	Salinity drop summary data				Regression: Rain total vs. salinity drop				Salinity drop:rain total
Site	Number Events	Avg. Salinity Drop	St. Dev.	St. Err.	p value	r^2	Slope	St. Err. Slope	LSD t-test
OK1	41	9.76	5.64	0.88	<0.0001	0.54	0.136	0.019	A
OK2	52	5.58	4.00	0.55	<0.0001	0.68	0.119	0.009	B
OK3	38	3.53	2.80	0.45	<0.0001	0.77	0.079	0.006	C
OK4	41	2.69	2.38	0.37	<0.0001	0.74	0.067	0.005	C
OK5	35	1.78	1.37	0.23	<0.0001	0.75	0.041	0.003	C
OK6	35	1.80	1.56	0.26	<0.0001	0.74	0.040	0.003	C
MR1A	24	7.01	4.96	1.01	<0.0001	0.65	0.127	0.018	A
MR1B	18	5.54	4.67	1.10	<0.0001	0.77	0.123	0.016	B
MR2	14	2.83	1.93	0.51	0.0077	0.46	0.060	0.018	BC
MR3	12	2.24	1.74	0.50	0.08	0.22	0.016	0.015	C
MR4	10	1.26	0.73	0.23	0.0099	0.54	0.020	0.006	C
MR5	12	1.34	1.05	0.30	0.147	0.20	0.016	0.010	C
BC1A	22	3.81	2.53	0.54	<0.0001	0.76	0.065	0.008	A
BC2A	22	2.52	2.28	0.49	<0.0001	0.61	0.055	0.009	B
BC3A	28	1.48	1.34	0.25	<0.0001	0.52	0.030	0.005	C
BC1B	23	3.37	2.73	0.57	<0.0001	0.60	0.072	0.012	A
BC2B	26	1.99	1.68	0.33	<0.0001	0.73	0.042	0.005	BC
BC4	19	1.35	1.14	0.26	<0.0001	0.83	0.029	0.003	C
BC5	19	1.28	0.94	0.22	<0.0001	0.81	0.024	0.002	C
BC6	8	1.01	1.20	0.42	0.0006	0.88	0.026	0.004	[1]
WC1A	28	2.90	2.83	0.53	<0.0001	0.45	0.062	0.012	AB
WC1B	29	2.34	1.35	0.25	<0.0001	0.64	0.043	0.006	AB
WC2	29	1.97	1.60	0.30	<0.0001	0.53	0.040	0.007	AB
WC3	24	1.31	0.93	0.19	<0.0001	0.77	0.028	0.003	A
WC4	27	1.18	0.81	0.16	<0.0001	0.57	0.021	0.004	AB
WC5	26	0.92	0.80	0.16	0.0004	0.40	0.017	0.000	B
HP1	5	6.36	6.46	2.89	0.0165	0.89	0.270	0.055	[1]
HP2	4	6.98	6.74	3.37	0.0273	0.95	0.252	0.004	[1]
HP3	4	4.39	1.59	0.79	0.0088	0.98	0.061	0.005	[1]
HP4	4	2.69	1.10	0.55	0.20	-	-	-	
HP5	3	3.07	0.68	0.39	0.75	-	-	-	
HP6	5	3.40	1.41	0.63	0.21	-	-	-	

[1] Too few events for meaningful comparison

Table 3. Model results and parameters for best regression model.

Slope = -0.0002*width – 0.29634*(% est. wet.) + 2.19439 * (% est. wet.)^2 + 0.04187*(% fr. wet.) + 1.45627*(% fr. wet.)^2 + 0.28130*(% imperviousness)

Summary		Model parameters	Estimate	t ratio	p
r^2	0.95	Intercept	-0.16248	-2.62	0.0161
RMSE	0.016	Width	-0.00020	-5.83	<0.0001
Mean	0.069	% estuarine wetlands	-0.29634	-4.12	0.0005
n	28	(% estuarine wetlands)^2	2.19439	3.47	0.0023
$F_{(6,21)}$	70.64	% freshwater wetlands	0.04187	1.01	0.3236
p	<0.0001	(% freshwater wetlands)^2	1.45627	8.70	<0.0001
		% imperviousness	0.28130	3.81	0.0010

Table 4. Summary of land use and land cover attributes for watersheds originating in or near Beaufort County, South Carolina. Bolded sections represent watersheds that were the primary focus of this study. Headwater sections are shown for select large watersheds. Color gradient depicts range from high (red) to low (green) values for each category.

	Land use and land cover % coverages				
Watershed	**Upland developed**	**Upland forest**	**Freshwater wetland**	**Estuarine wetland**	**Water**
Broad Creek	21.5	40.3	7.5	14.6	9.4
May River	9.8	29.0	17.7	20.3	15.7
May River (headwaters)	**11.4**	**34.0**	**29.6**	**5.4**	**4.5**
Okatie and Colleton Rivers	16.4	27.3	16.3	16.5	12.4
Okatie River (headwaters)	**18.7**	**25.8**	**26.8**	**6.3**	**4.5**
Wright River	0.6	12.1	32.4	40.2	5.6
Village Creek	1.2	43.6	17.3	25.2	4.9
Wallace (Capers) Creek	**2.1**	**32.6**	**16.7**	**26.1**	**7.3**
Battery Creek	**21.7**	**32.1**	**7.3**	**21.1**	**12.0**
Chechesse River	1.1	36.5	32.1	16.8	8.3
Chechesse River (headwaters)	0.7	41.5	42.9	6.1	2.5
Euhaw Creek	0.5	39.3	43.1	6.0	3.6
Albergottie Creek	22.9	25.1	15.2	17.7	5.1
Harbor River	2.9	40.7	16.6	13.1	14.0
McCalleys Creek	4.2	19.7	19.0	21.4	21.3
Huspah Creek	**1.6**	**27.1**	**40.9**	**6.9**	**11.2**
Pocotaligo River	2.2	39.7	34.8	7.2	5.4
Tulifiny River	0.9	30.4	47.2	9.6	4.4
Morgan River system	4.5	25.8	11.9	36.6	15.2
Morgan River (headwaters)	5.7	20.1	12.9	40.9	17.9
Boyd Creek system	0.3	32.4	17.2	28.1	17.7
AVERAGE	7.2	31.2	24.1	18.4	9.7

Table 5. Summary of soil classification attributes for watersheds originating in or near Beaufort County, South Carolina. Bolded sections represent watersheds that were the primary focus of this study. Headwater sections are shown for select large watersheds. Color gradient depicts range from high (red) to low (green) values for each category.

Watershed	Soil classification % coverages				
	Somewhat poor	Poor	Very poor	Poor and very poor	All poor categories
Broad Creek	18.8	22.7	19.7	42.4	61.2
May River	25.5	16.8	31.3	48.0	73.6
May River (headwaters)	**10.2**	**2.7**	**24.5**	**27.2**	**37.4**
Okatie and Colleton Rivers	19.8	25.5	26.0	51.5	71.2
Okatie River (headwaters)	**13.5**	**2.4**	**39.0**	**41.4**	**54.9**
Wright River	7.1	11.3	67.5	78.7	85.8
Village Creek	28.9	12.9	33.0	46.0	74.8
Wallace (Capers) Creek	**36.5**	**5.6**	**36.6**	**42.2**	**78.7**
Battery Creek	**30.6**	**8.5**	**28.1**	**36.6**	**67.2**
Chechesse River	7.0	33.3	30.4	63.7	70.7
Chechesse River (headwaters)	25.7	1.7	43.3	45.0	70.6
Euhaw Creek	17.5	25.6	25.9	51.5	69.0
Albergottie Creek	22.6	17.6	25.7	43.3	66.0
Harbor River	8.2	27.2	22.9	50.1	58.3
McCalleys Creek	13.3	13.4	33.7	47.1	60.4
Huspah Creek	**14.3**	**36.3**	**22.7**	**59.0**	**73.3**
Pocotaligo River	16.3	30.1	20.9	51.0	67.3
Tulifiny River	13.3	25.4	31.4	56.9	70.2
Morgan River system	15.3	11.4	42.9	54.3	69.6
Morgan River (headwaters)	8.5	16.9	10.8	27.7	36.2
Boyd Creek system	10.7	18.3	38.6	56.9	67.7
AVERAGE	17.3	17.4	31.2	48.6	65.9

Table 6. Summary of geophysical attributes for watersheds originating in or near Beaufort County, South Carolina. Bolded sections represent watersheds that were the primary focus of this study. Headwater sections are shown for select large watersheds. Color gradient depicts range from high (red) to low (green) values for each category.

	Geophysical characteristics						
Watershed	**Area (km^2)**	**Width at mouth (m)**	**Perimeter (km)**	**Depth at mouth (m)**	**Elevation range (m)**	**Mean elevation (m)**	**Mean salinity (psu)**
Broad Creek	68	268	44	-6	13	2	29
May River	103	615	60	-11	26	4	30
May River (headwaters)	**79**	**230**	**46**	**-4**	**47**	**4**	**30**
Okatie and Colleton Rivers	151	687	68	-11	22	4	31
Okatie River (headwaters)	**49**	**273**	**68**	**-3**	**26**	**5**	**30**
Wright River	108	317	69	-4	16	2	24
Village Creek	21	137	25	-4	11	3	27
Wallace (Capers) Creek	**19**	**109**	**31**	**-5**	**15**	**2**	**32**
Battery Creek	**32**	**132**	**33**	**-9**	**13**	**3**	**31**
Chechesse River	113	629	57	-9	47	3	30
Chechesse River (headwaters)	56	235	73	-4	24	6	26
Euhaw Creek	88	212	48	-5	32	6	31
Albergottie Creek	22	252	35	-2	17	5	32
Harbor River	8	69	17	-4	16	5	30
McCalleys Creek	16	214	26	-2	16	2	31
Huspah Creek	**63**	**306**	**46**	**-3**	**18**	4	25
Pocotaligo River	128	197	80	-1	20	4	22
Tulifiny River	39	176	53	-1	20	5	14
Morgan River system	73	514	54	-7	13	2	30
Morgan River (headwaters)	24	319	33	-8	12	1	25
Boyd Creek system	42	403	33	-6	13	2	29
AVERAGE	62	300	48	-5	21	4	28

Table 7. Series of models used to investigate relationship between slope (salinity drop per mm rainfall) and various watershed-scale variables. Due to the low sample size, the risk of overfitting increases as the number of model variables increases.

y = slope of salinity drop per rainfall mm

Summary		Model parameters	Estimate	t ratio	p
r^2	0.9422	Intercept	0.3432	10.58	0.0018
RMSE	0.024	% estuarine wetlands	-0.0117	-6.99	0.0060
Mean	0.129				
n	5				
$F_{(1, 3)}$	48.9				
p	0.006				

Summary		Model parameters	Estimate	t ratio	p
r^2	0.9918	Intercept	0.1958	4.35	0.0491
RMSE	0.011	% estuarine wetlands	-0.0178	-9.42	0.0111
Mean	0.129	% very poorly drained soils	0.0088	3.47	0.0740
n	5				
$F_{(2, 2)}$	120.45				
p	0.0082				

Summary		Model parameters	Estimate	t ratio	p
r^2	0.999	Intercept	0.1520	14.73	0.0431
RMSE	0.002	% freshwater wetlands	-0.0066	-7.45	0.0849
Mean	0.129	% estuarine wetlands	-0.0414	-12.95	0.0491
n	5	% very poorly drained soils	0.0028	10.45	0.0608
$F_{(3,1)}$	2289				
p	0.0154				

Table 8. Series of models used to investigate relationship between headwater salinity drop (averaged for all events studied) and various watershed-scale variables. Due to the low sample size, the risk of overfitting increases as the number of model variables increases.

y = average salinity drop for all events

Summary		Model parameters	Estimate	t ratio	p
r^2	0.922	Intercept	2.0125	2.73	0.0717
RMSE	0.904	Area (km^2)	0.0500	5.98	0.0094
Mean	5.694				
n	5				
$F_{(1, 3)}$	35.78				
p	0.0094				

Summary		Model parameters	Estimate	t ratio	p
r^2	0.984	Intercept	1.3901	3.00	0.0953
RMSE	0.4986	% poorly drained soils	0.0650	2.80	0.1073
Mean	5.694	Area (km^2)	0.4209	7.78	0.0161
n	5				
$F_{(2, 2)}$	62.67				
p	0.0157				

Summary		Model parameters	Estimate	t ratio	p
r^2	0.999	Intercept	1.5250	37.70	0.0169
RMSE	0.043	% poorly drained soils	0.0590	29.20	0.0218
Mean	5.694	Area (km^2)	0.0708	39.33	0.0162
n	5	Width at mouth (m)	-0.0058	-16.50	0.0385
$F_{(3,1)}$	5798				
p	0.0097				

Table 9. Model results for full three-variable models predicting headwater sensitivity as measured by slope (salinity drop per mm rainfall) and average salinity drop. All six models were tested, and the results were scored into top 25% (most sensitive) and bottom 25% (least sensitive). The total score across all models is the combined rank score. A score of -6, for instance, indicates that the bottom 25% was predicted in all 6 models, whereas a score of 3 indicates that the watershed was in the top 25% for 3 of the 6 models.

	Statistical modeling results						
Watershed	**Observed slope**	**Model estimate slope**	**% error**	**Observed average drop**	**Model estimate drop**	**% error**	**Combined 25% rank score**
Broad Creek		0.830			6.114		0
May River	**0.125**	**0.125**	**0.000**	**6.250**	**6.245**	**-0.081**	**0**
Okatie and Colleton Rivers	**0.136**	**0.134**	**-1.471**	**9.760**	**9.778**	**0.185**	**3**
Wright River		0.281			8.012		3
Village Creek		0.000			2.981		-5
Wallace (Capers) Creek	**0.050**	**0.050**	**0.000**	**2.600**	**2.604**	**0.161**	**-6**
Battery Creek	**0.065**	**0.066**	**1.538**	**3.500**	**3.550**	**1.425**	**0**
Chechesse River		0.148			7.851		2
Euhaw Creek		0.388			8.040		4
Albercottie Creek		0.083			2.671		-3
Harbor River		0.180			3.317		0
McCalleys Creek		0.142			2.196		-3
Huspah Creek	**0.270**	**0.270**	**0.000**	**6.360**	**6.357**	**-0.052**	**3**
Pocotaligo River		0.245			11.217		5
Tulifiny River		0.376			4.747		3
Morgan River system		0.000			4.384		-3
Boyd Creek system		0.023			3.277		-3

Table 10. Watershed characteristics related to stormwater runoff modeling. Dev. is Development shown as percentage of watershed area, IC is Impervious Cover, and CN is Curve Number - the higher the values the greater the runoff; I_a is Initial Abstraction and reflects the amount of rain needed for runoff to begin; HSG is Hydrologic Soil Group, and C and D are the most impervious of the soil groups.

Watershed	Area		Dev.	IC	CN		I_a (in)	HSG
	Ac	Ha		%	0.20	0.05	($CN_{0.05}$)	C+D
WC1a	1,013	410	7%	3	70.5	59.2	0.34	60%
WC1b	596	241	1%	1	72.5	61.9	0.31	70%
WC2	1,707	691	4%	2	71.8	60.9	0.32	64%
WC3	2,585	1,046	4%	2	73.2	62.8	0.30	63%
WC4	3,498	1,416	3%	2	74.3	64.3	0.28	66%
WC5	4,804	1,944	2%	1	75.3	65.8	0.26	69%
BC1a	58	23	13%	5	70.4	59.0	0.35	39%
BC2a	712	288	57%	30	78.4	70.1	0.21	27%
BC3a	1,419	574	47%	24	76.5	67.4	0.24	40%
BC1b	1,023	414	16%	8	71.1	60.0	0.33	50%
BC2b	1,924	779	25%	14	73.5	63.2	0.29	52%
BC4	4,151	1,680	30%	17	75.2	65.6	0.26	48%
BC5	5,050	2,044	30%	16	75.3	65.8	0.26	50%
BC6	7,979	3,229	24%	13	76.6	67.6	0.24	61%
OK1	4,713	1,907	44%	26	80.0	71.9	0.20	90%
OK2	5,339	2,161	42%	24	79.9	71.8	0.20	91%
OK3	5,673	2,296	40%	23	80.2	72.5	0.19	91%
OK4	7,189	2,909	41%	21	80.3	72.7	0.19	91%
OK5	11,565	4,680	33%	17	79.1	70.5	0.21	92%
OK6	12,008	4,859	32%	17	79.3	70.8	0.21	92%
MR1a	5,984	2,422	15%	8	76.0	66.7	0.25	78%
MR1b	4,253	1,721	40%	20	78.3	69.9	0.22	72%
MR2	10,819	4,378	24%	13	76.7	67.7	0.24	74%
MR3	11,616	4,701	22%	12	76.6	67.6	0.24	74%
MR4	13,732	5,557	20%	10	76.5	67.4	0.24	74%
MR5	15,056	6,093	19%	10	76.6	67.5	0.24	74%

Table 11. BMP and development scenarios for the subwatersheds in each system identified as more volume sensitive. IC is Impervious Cover, Dev. Is Developed, and CN is Curve Number – the higher the values the greater the runoff; I_a is Initial Abstraction and reflects the amount of rain needed for runoff to begin; af is acre feet; and Ratio is proportion of rainfall converted to runoff. Target Retrofit is the development level at which minimum degradation to water quality occurs. 50% Build Out is projecting additional watershed development for half of all dry land not yet developed. 100% Build Out projects for all of dry land not yet developed. Target Volume Reduction is volume of runoff required to be reduced in order to reach Target Retrofit scenario.

Watershed & Area (ha)	Development Scenario	IC	Dev.	CN 0.20	CN 0.05	I_a (in) ($CN_{0.05}$)	Runoff - 1.95" rain Volume (af)	Runoff - 1.95" rain Ratio	Target Volume Reduction (af)
WC1a	Current Development	3%	7%	71	59	0.34	26	0.16	–
410	Target Retrofit	9%	27%	74	65	0.27	33	0.20	–
	50% Build Out	16%	38%	77	68	0.24	38	0.23	5
	100% Build Out	29%	69%	83	76	0.16	55	0.34	22
WC1b	Current Development	1%	1%	72	62	0.31	17	0.18	–
241	Target Retrofit	9%	21%	76	66	0.25	21	0.22	–
	50% Build Out	18%	28%	77	68	0.23	23	0.24	2
	100% Build Out	35%	55%	82	75	0.17	31	0.32	10
BC2a	Current Development	30%	57%	78	70	0.21	30	0.26	16
288	Target Retrofit	9%	30%	67	54	0.42	14	0.12	–
	50% Build Out	35%	66%	82	75	0.16	37	0.32	23
	100% Build Out	40%	74%	86	81	0.12	47	0.41	33
BC1b	Current Development	8%	16%	71	60	0.33	27	0.16	–
414	9% Impervious Cover	9%	25%	73	62	0.30	30	0.18	–
	50% Build Out	20%	41%	77	68	0.24	39	0.23	9
	100% Build Out	32%	66%	83	76	0.16	55	0.33	25
OK3	Current Development	23%	40%	80	73	0.19	266	0.29	45
2,296	Target Retrofit	9%	25%	77	69	0.23	221	0.24	–
	50% Build Out	30%	51%	82	75	0.17	294	0.32	73
	100% Build Out	36%	63%	83	77	0.15	325	0.35	104
MR2	Current Development	13%	24%	77	68	0.24	408	0.23	10
4,378	Target Retrofit	9%	24%	76	67	0.24	398	0.23	–
	50% Build Out	23%	42%	80	72	0.19	491	0.28	93
	100% Build Out	33%	61%	83	76	0.16	592	0.34	194

Table 12. Climate scenarios for the watersheds identified as the most volume sensitive. CN is Curve Number – the higher the value the greater the runoff; I_a is Initial Abstraction and reflects the amount of rain needed for runoff to begin; af is acre feet and Ratio is proportion of rainfall converted to runoff. Current Conditions reflects average antecedent runoff conditions and 1.95 inch rain. Both Climate Scenarios increase rainfall by 15%. Climate 1 reflects semi-wet runoff conditions, and Climate 2 reflects wet runoff conditions.

Watershed & Area (ha)	Climate Scenario	CN 0.20	CN 0.05	I_a (in) ($CN_{0.05}$)	Runoff - 1.95" rain Volume (af)	Runoff - 1.95" rain Ratio
WC1a	Current Conditions	71	59	0.34	26	0.16
410	Climate 1	78	70	0.22	54	0.29
	Climate 2	86	81	0.12	84	0.44
WC1b	Current Conditions	72	62	0.31	17	0.18
241	Climate 1	80	72	0.20	35	0.31
	Climate 2	87	82	0.11	53	0.48
BC2a	Current Conditions	78	70	0.21	30	0.26
288	Climate 1	84	79	0.14	55	0.41
	Climate 2	90	87	0.07	77	0.58
BC1b	Current Conditions	71	60	0.33	27	0.16
414	Climate 1	79	70	0.21	56	0.29
	Climate 2	86	81	0.12	87	0.45
OK3	Current Conditions	80	73	0.19	266	0.29
2,296	Climate 1	86	81	0.12	470	0.44
	Climate 2	91	89	0.06	646	0.61
MR2	Current Conditions	77	68	0.24	408	0.23
4,378	Climate 1	83	77	0.15	769	0.38
	Climate 2	89	86	0.08	1108	0.55