Developing Coastal Plain Ecological Flow Guidance in the Albemarle-Pamlico Basin: Trent River Pilot Study

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1. Executive Summary

Ecological flows of inland freshwater rivers are those that maintain ecological integrity and are embodied in policies for planning and management of water withdrawals. This report focuses on how low flows may alter water quality, habitat distribution and community structure. Specifically, we describe a study on the Trent River, NC, in the context of broader efforts on policy. Rivers within coastal plains present issues regarding ecological flows different from those within piedmont and mountain watersheds. These issues are addressed with special reference to the Albemarle Pamlico Sound region.

Low flow conditions, their causes, and consequences are linked to elevation, land and water use, and meteorology. Elevation above sea level is critical to how ecological flows are understood. In the mountains, piedmont and upper coastal plain, low flow is generally inferred to alter habitat through vertical changes in river stage. A decrease in water level changes the distribution of riverine habitats and the communities of fishes, invertebrates, and other organisms. However, in the lower coastal plain, sea level begins to affect stage and habitats as the river approaches base level. Low flows in this region are less likely to have a major influence on water levels but may influence water quality due to the increased likelihood of saltwater intrusion during low flow conditions along tidal reaches. Salinity, dissolved oxygen, and temperature are water quality parameters that are likely to alter habitat. Further, human relationships to waterways and riparian land use may change as elevation approaches sea-level.

We utilized a transdisciplinary approach to evaluate the influence of low flows on coastal plain river ecosystems. The disciplines include hydrology, geography, ecology and sociology. This pilot study was conducted on the Trent River, a tributary to the Neuse River Estuary. The Trent River was selected by the APNEP Ecological Flows Action Team as an ideal location for a pilot project due to the availability of flow, water quality and ecological data; a diversity of land use and water users; its proximity to the coast; and interest from the NC Department of Environmental Quality. Historical data on flows, water levels, water quality and fauna have been assessed relative to drought periods causing low flows. These data supplement an intensive longitudinal study of water levels and conductivity during the drought of 2021-2022.

The geospatial component of the study provided georeferenced context for other components. The hydrology component monitored flows, water levels and conductivity along the Trent River for nearly two years. Head of tide was identified and was upstream of measured saltwater intrusion. Low flows along the Trent River were observed to (1) disconnect water level from discharge and (2) promote inland saltwater intrusion. Downstream effects from estuaries and neighboring rivers on coastal plain river dynamics are underappreciated and shown to be important. The ecological component, thus far, has identified potential salinity thresholds of impact from the literature. Specifically, we have estimated consensus thresholds for wetland trees and fish species when experiencing repeated exposure to oligohaline or saltier conditions. For wetland trees a threshold of 2 ppt begins to impact the most sensitive species, life history stages, and ecological processes. A threshold of 6 ppt begins to show mortality and significant other detrimental impacts to plant physiological water-use processes. Fish habitat was estimated to be optimum for most appropriate species when salinity was $\leq$ 2 ppt and suitable when $\leq$ 5 ppt.

The human dimension component assessed ecological policies within North Carolina and the United States. Further, few studies have incorporated stakeholder preferences into frameworks designed to determine policies for management of low flows. Surveys were distributed among eastern North Carolina water users to determine perceptions of change in flow conditions over time, consumptive and non-consumptive water uses, and preferences regarding potential policy actions. This transdisciplinary approach is considered as a model for addressing not only ecological flows within coastal plain rivers and watersheds but other socio-ecological issues. In light of growing water demands, land use, and climate change, there is an increased risk that low flow conditions can impact coastal aquatic ecosystems. Broader efforts are needed to organize stakeholders to develop support and strategies to advance system-wide policies related to ecological flows for the Albemarle-Pamlico Drainage Basin. The Albemarle- National Estuary Partnership (APNEP) is positioned to be a leader in expanding efforts not only on ecological flows in coastal plain rivers but also broader issues of water management across the spectrum of flows.

Contents

2. Introduction

This report is intended to provide general guidance for ecological flow program development in the Albemarle-Pamlico Estuarine System (APES), utilizing examples from the literature and data collected from the Trent River Watershed. Emphasis has been placed on the tidal region of the river and importance of downstream conditions. The Trent River was selected by the APNEP Ecological Flows Action Team as an ideal location for a pilot project due to the availability of flow, water quality and ecological data; a diversity of land use and water users; its proximity to the coast; and interest from the NC Department of Environmental Quality. The report is presented in the following order: review of policies and practices across states and within North Carolina, results from the Trent River study in the context of developing ecological flow criteria for APES, and recommendations for future research and policy development.

Interrelationships between water flow, environmental conditions and human use have long been recognized. In the 20th century, developed nations with emphasis on public health and natural resource management developed rules and regulations focused on maintaining minimal flows to promote high concentrations of dissolved oxygen, integrity of water supply, and health of selected fish species stocks. These rules often identified a single, constant minimal flow for a system that addressed the specific societal concerns. Toward the end of the 20th and into the 21st centuries, a growing number of agencies and NGOs realized that more holistic approaches would be needed to address multiple environmental concerns associated with low flows.

Various terms refer to the relationship between flow and ecosystem properties and associated assessment approaches. Some of these terms may have legal meaning within specific jurisdictions. *The term "ecological flow" broadly refers to the quantity, quality, and timing of water discharge that is necessary to maintain riparian and estuarine ecosystems, as well as the reliance on these ecosystems by humans for their livelihoods and well-being* (Greco et al., 2021). The term “environmental flow” is, also, used. One distinction is that environmental flow sustains the minimum flow that is crucial not only for ecosystems but also for the growth of economic activities, while the ecological flow assures the preservation of river basin ecosystems (Vélez, 2015). Environmental flow is additionally known as instream flow needs or instream flows (Alberta government, n.d) that include both "instream flows"—flows in a river or stream—and "freshwater inflows"—flows of fresh water that enter an estuary system through a river or stream (Texas Living Waters Project, 2017). According to the Texas Parks and Wildlife Department (TPWD, n.d.), water flowing in a stream channel is the simplest definition of instream flow. The phrase "instream flow" also refers to flowing water that maintains riparian (stream bank) and floodplain ecosystems, as well as a broader stream ecosystem. Natural stream flows change with the seasons, so instream flows typically fluctuate from month to month rather than having a constant flow rate throughout the year (Washington State Department of Ecology, n.d). Terms of flow dynamics have, also, been dually connected to both ecological and human needs. An instream flow study aims to determine the best flow patterns that preserve fish and wildlife resources while simultaneously offering long-term advantages for other uses of water by humans (TPWD, n.d).

North Carolina currently has no laws that directly address ecological flows. The most important State law for our purposes is the Water Use Act of 1967. As stated by the North Carolina Department of Environmental Quality (DEQ), the Water Use Act of 1967, which only applies to authorized Capacity Use Areas, is now the sole law in North Carolina that explicitly restricts withdrawals. Regarding relative rights of riparian users, the Act does not affect or amend existing common or statute law. The NC Division of Water Resources (DWR) is entitled to designate a "capacity usage area" if it follows particular and comprehensive processes defined in the Act. The Central Coastal Plain Capacity Use Area (CCPCUA) and related regulations, which cover 15 counties in North Carolina, were established as a result of the over pumping of key aquifers in the Coastal Plain. The CCPCUA laws mandate annual registration of water intake for users who use more than 10,000 gallons of ground water or surface water per day, and a permit for those who withdraw more than 100,000 gallons of ground water per day (NCDEQ, n.d). The decision by the DWR that a raindrop is in a "capacity use area" is the first step necessary to prove that a raindrop is in the public interest (Aycock, 1967). Following the designation of a "capacity use area," the DWR may go on to establish rules for the use of water, including scheduling of withdrawals, protection against or reductions of saltwater intrusion, and pumping levels or maximum pumping rates or both. Before the DWR makes a decision, there must once again be notice and a hearing on the regulations. In all cases where consumption exceeds 100,000 gallons per day, water users in "capacity use areas" are obliged by law to get a permit from the DWR. The DWR can approve or disapprove a permit for consumption that exceeds 100,000 gallons per day if the usage is consumptive. The DWR is obligated to provide a permit without a hearing and without applying any limitations that it may attach to a permit for a consumptive use if the use is non-consumptive. (Non-consumptive use in this context refers to the use of water withdrawn from a stream, groundwater system, or aquifer in a way that ensures its return to the stream without noticeably degrading in quantity or quality and has no adverse effects on nearby water users. Consumptive use refers to any use of water withdrawn from a stream or the ground that is not non-consumptive). Although they are not obliged to obtain a permit, water users in "capacity use areas" who do not exceed 100,000 gallons per day must nonetheless abide by the DWR’s rules for water usage in the region, except for domestic water use (Aycock, 1967). Although, it appears that the Water Use Act of 1967 is the only statute in North Carolina that specifically restricts withdrawals as of early 2023, the DWR may include restrictions governing withdrawals and instream flows while reviewing various other potential permits.

Assessment methods that can be used for planning across the whole state are necessary for the DWR's extensive river basin planning program. River basin hydrologic models would benefit from ecological flow assessments at each place of interest to estimate current and future water availability (NCDEQ, n.d). The gap in North Carolina's policymaking regarding ecological flows is something we are attempting to explore in this report.

NC Session Law 2010-143 was approved in reaction to growing concerns over water availability in North Carolina. This law required NC DEQ to create basin-wide hydrological models for each of North Carolina’s 17 river basins to evaluate if there is adequate water for all demands and to estimate the places, times, and frequencies at which ecological flows may be adversely affected in North Carolina (NC DEQ 2013). In this case, ecological flow is defined as “stream flow necessary to protect ecological integrity” and ecological integrity is defined as “the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system” (NC DEQ 2013).

Early efforts (NC DEQ 2013) to develop ecological flow guidance in NC were limited to the Mountain and Piedmont provinces. Limited guidance was available for Coastal Plain watersheds. Ecological flows have most commonly been applied to waterways that have a clear relationship between discharge and river stage. These conditions tend to be in systems significantly above sea level where river slope promotes unidirectional flows. Such systems have the best opportunity to be gaged that allows good flow estimates through stage. Hydrological models are built from these flows and other information. These models provide reasonable predictive power of flow based on meteorological, watershed, and human use conditions. Such models have been constructed for North Carolina water-resource management. These include OASIS and Waterfall models (NC DEQ 2013) Mountain, Piedmont and Upper Coastal Plain rivers in North Carolina generally meet these criteria. Therefore, the models are limited to these regions.

Recent work in North Carolina has suggested that flow patterns along North Carolina's Coastal Plain rivers have been changing over time (Weaver 2015, Meitzen 2016, Ledford et al. 2020), with minimum flows becoming lower over time (7Q10 and 10^{th} percentile flows). Similarly, Fleming et al. (2021) found declines in the annual 7-day minimum flow from 1939-2013 along Coastal Plain streams in the Chesapeake Bay watershed. The declines in flow minimums during low flow periods have been attributed to a range of factors including increased water use, greater evapotranspiration, the occurrence of several severe droughts in the early 2000s, increased variability in summer precipitation, and a decline in summer precipitation in the region. These studies support the importance of the establishment of ecological flow criteria to assist with low flow management.

Low flows (the flow in streams during prolonged dry weather periods) have an important influence on aquatic ecosystems because of their influence on contaminant dilution, saltwater intrusion, and aquatic habitat (Price et al. 2011). Although there are broader considerations for ecological flows (timing, duration, and range of streamflows), the occurrence of floods and overbank flows is less likely to be affected by water withdrawals when compared to low flows. Therefore, this project focused on the low flow aspect of ecological flows for coastal watersheds, utilizing specific examples from the Trent River watershed and the broader literature, to provide guidance for watershed-based ecological flow management for coastal watersheds in North Carolina.

3. Water Use Policy and Ecological Flows

3.1 Water Withdrawal Allocation Regulation

States are generally in charge of water allocation as there is little federal legislation on water allocation. Certain uses of water, such as water flows from one watershed to another, groundwater withdrawal from overused aquifers, water dams, and well construction, are governed by state statutes and regulatory frameworks (National Agricultural Law Center, n.d).

North Carolina is one of three coastal states (along with Alabama and Louisiana) that do not currently have legally enforced environmental instream flow criteria, despite the ecological importance of the state's rivers and the multiple threats to those values, including an uncertain water supply, rising water demand, and habitat change (Whisnant and Holman 2008, Praskievicz, 2018).

There are two main water use allocation schemes in the United States. The riparian doctrine, which is dominant in the eastern United States' water-rich region, is the first. The second is the "first-in-time, first-in-right" system of prior appropriation, which is prevalent in the largely arid western United States (National Agricultural Law Center, n.d). The riparian doctrine system of water rights was brought over to the eastern United States by English Common Law. When water was abundant, and population density was low, this approach may manage water problems, but it has typically failed to do so during droughts or when demand from population expansion, irrigation, recreation, and industry has increased (Smolen et al., 2017). Due to the lack of water in the area, the prior appropriation doctrine, sometimes known as "first in time - first in right," developed in the western United States (Gopalakrisnan, 1973). Also, a small number of states have implemented a hybrid system that combines elements of the riparian system and the prior appropriation doctrines (National Agricultural Law Center, n.d).

3.2 Riparian Doctrine Water Rights (Eastern States)

The riparian doctrine popular in Eastern US to decide who has the legal right to utilize water (Atkinson & Lake, 2020). The main premise of the riparian doctrine is that the right to use water belongs to the owner of land that is close to a body of water (such as a lake, river, or stream). A riparian landowner may file a lawsuit against another riparian landowner if the first landowner claims the second landowner is obstructing his or her usage of a shared body of water. The right to use water under the riparian doctrine often does not take the type of usage into account (NDSU, 2014).

Some states' water allocation policies account for both surface water and groundwater withdrawals. Georgia and Mississippi are among the Southeastern states with laws governing the allocation of both surface water and groundwater (Mississippi Code § 51-3-3, 2019). The Georgia General Assembly has passed a wide range of laws that govern various facets of water use in the state throughout the last 40 years. Two acts, the Groundwater Use Act of 1972 (Ground Water Act) [FN421] and an amendment to the Georgia Water Quality Protection Act of 1964 from 1977, specifically address the allocation of water to certain uses through the provision of permits for the use of water (Protection Act). The first statute relates to users of groundwater, and the second to users of surface water, and both impose comparable permission procedures (Dellapenna, 2005).

Florida, Virginia, and South Carolina have water withdrawals and instream flow preservation rules in place as well (U.S. Code, Code of Virginia, 2021) (Winemiller, 2005). To control water consumption, Florida has a distinctive and intricate two-tiered appropriation system. In the past, Florida courts have applied the idea of riparian rights to disputes involving water rights, but in 1974, two years after a detailed statutory permitting program was passed, all unexercised riparian rights were statutorily extinguished (Smolen et al., 2017). More than 20 independent volunteer scientists and engineers from South Carolina colleges gathered in Columbia in 2008 to hear testimony and assess the effectiveness of potential minimum instream flow regulations to be adopted by the state (Graf, 2009), which were subsequently enacted in 2011 (SCDHEC, 2012). The 2011 revisions to the South Carolina Surface Water Withdrawal, Permitting, Use, and Reporting Act provide for instream flow regulations to "maintain the biological, chemical, and physical integrity of the stream…" (S.C. Code, 2012; Table 1). The instream flow rule is adjusted throughout the year based on percentages of the mean annual daily flow (Ibid).

Among Northeastern states, Connecticut was the first to pass a statute ensuring the protection of environmental flows for Connecticut's "stocked streams"—i.e., rivers and streams that the Division of Wildlife has stocked with fish by the state legislature in 1971 (Table 1). The legislature updated this statute in 2005 in response to requests from environmentalists and with the support of water users requiring the Department of Environmental Protection (DEP) to create environmental flow regulations for all rivers and streams in the state while also making provisions for other water uses (Kendy et al., 2012). Maryland and New Jersey passed surface water allocation regulations in 1988 and 1990, respectively (7 DE Code § 6003, 2018), (N.J.A.C. 7:19, 2005). These regulations stipulate that a permit must be granted before anybody in Maryland builds a facility, building, or structure that uses more than 10,000 gallons per day of surface water or groundwater on a yearly average for agricultural purposes (Ellixson & Everhart, 2016). In New Jersey, this limitation is in excess of 100,000 gallons per day (NJDEP, 2022).

The Massachusetts Water Management Act (WMA) of 1987 established a system for water withdrawal permits in response to concerns regarding water quality and quantity. Twenty years later, the Act's implementation had not achieved its water withdrawal goals, as evidenced by the ongoing effects of stream depletion. As a result, environmental advocacy groups filed legislation demanding the establishment of environmental flow protection criteria and appealed permit decisions for failing to protect rivers and streams from excessive water withdrawals appropriately. The Massachusetts Sustainable Water Management Initiative (SWMI) was established by the state in 2009 in response to ongoing debate (EOEEA, 2015).

Beginning in the 2000s, the remaining Northeastern states, including Maine, Rhode Island, New Hampshire, and New York, also implemented water allocation rules for instream flows (NHDES, 2015), (601.7NY-CRR, 2017). Maine's state government passed statutory law in 2002 to allow for the estimation of flow criteria and water levels following numerous years of drought in the 1990s and the early 2000s. Maine was the first US state to enact statewide environmental flow standards in 2007 based on the concepts of conserving aquatic life resources and significant hydrological processes. No new permitting system was established for water extraction, flow, or water level adjustment in the 2007 statute; rather, new rules link ecological aims to environmental flow criteria for groundwater. Permits that were in effect before 2007 are not modified (Maine Department of Environmental Protection, n.d). In Rhode Island, the Water Allocation Program Advisory Committee (WAPAC) was established by the Water Resources Board (WRB) in 2002, and a comprehensive water allocation planning initiative was started. The Committee suggested, and the board approved in March 2004, the formation of the Streamflow Working Group, a collaboration between the WRB and the Rhode Island Department of Environmental Management (DEM) to address streamflow issues like aquatic base flow and the advancement of a statewide streamflow gaging network (Kendy et al., 2012).

In several eastern states, notably Georgia, the notion of "regulated riparianism" is developing legally. Riparian rights are a subset of common property in which riparian owners have an equal right to the water from a common source and are free to use the resource whenever they deem proper. Every owner benefits fully from any additional usage, but all owners share in the cost of the benefit. Regulated riparianism regards water as a public resource that is subject to control and management by the state, in contrast to conventional riparian rights, which accord each riparian landowner with equal rights to the water in a stream or river that runs through their property (Dellapenna, 2005). Many knowledgeable commentators now refer to eastern water law as "regulated riparianism," as legislatures in other eastern US states have kept refining the common law doctrine of riparianism. The withdrawal permission requirement, rather than the riparian nature of the usage, is where the regulated riparian legislation most fundamentally differs from common law riparian rights. The concept of equitable use is treated considerably differently under regulated riparianism than it is under common law. The most significant distinction is that an administering agency determines whether a use is appropriate before it is implemented, considering both general social policy and how the proposed use would influence other authorized applications (Dellapenna, 2002). Currently, practically all riparian states, including North Carolina, have made the transition to water allocation through a permit system, commonly referred to as a "regulated riparian" system. Users, quantity, and duration of water usage are all subject to restrictions under the controlled riparian system. Regulated riparianism is distinct from common law riparianism in that it accounts for anticipated consumption before any actual use of water is made (National Agricultural Law Center, n.d).

3.3 Prior Appropriation Doctrine Water Rights (Western States)

The doctrine of prior appropriation evolved gradually in the western United States. Many western streams had erratic flows that made it difficult to adhere to the riparian doctrine's requirements. For instance, by the early to mid-1800s, Utah's growing population of Mormon migrants necessitated finding a solution to the state's relatively limited water supply in the face of an expansion of agriculture. Utah’s state government devised a water allocation system that encouraged shared use of that resource with a philosophy that supported good usage in response to the need and their religious convictions. However, the "prior appropriation doctrine" eventually took the role of the beneficial use ideology (Arthur, n.d). Prior appropriation grants water rights depending on the date, location, and purpose of use. It permits the redirection of water from its source to satisfy water rights and determines who receives water during times of scarcity. Rights are granted based on a priority date under prior appropriation. A claim's validity increases with age; senior water rights are frequently connected to farming, ranching, and other agricultural purposes. Contrary to riparian rights, however, owners of rights may eventually lose access via inactivity (UNR, 2020).

Since the effort to recognize water rights for non-consumptive instream uses began in the mid-1970s, every western state has put in place, in one form or another, systems for identifying and protecting non-consumptive instream uses of water. Instream flow rights can be requested or established in all western states and have been for many years (Amos & Swensen, 2015). Since its state legislature passed the minimum perennial stream flow program in 1955, Oregon has acted as a pioneer in the field of instream preservation. The 1987 Instream Water Rights Act, which places instream water rights on an equal basis with all other water rights, was enacted by the Oregon legislature to modernize instream protection and recognize the environmental benefits of keeping water in a water body (Amos, 2009). With the historic Instream Water Rights Act of 1987, Oregon became the first western state to recognize instream flow rights under state law that considered fish and wildlife needs, recreation, water quality, and pollution abatement, thereby amending the concept of beneficial use under state appropriative law. Despite the particulars and quirks of each state's instream flow programs, we can see that much has changed since the 1970s in the way that western states have addressed and protected significant non-consumptive uses of water (Amos & Swensen, 2015).

Washington state passed the Minimum Water Flows and Levels Act in 1967, though instream flows were not widely adopted in state watercourses until the Department of Ecology established the Washington Instream Resources Protection Program in 1979 (Barwin et al. 1988). Since 1987 each water right has a priority date that establishes its position in comparison to all other rights from the same (or connected) source (Washington State Department of Ecology, n.d). In addition to surface water regulations, a water resource management rule was recently enacted to stop further losses in flow brought on by ground water withdrawals (Amos & Swensen, 2015).

Additionally, Alaska and Hawaii have water permit regulations (Table 1). Alaska’s instream rights are unique because private parties are allowed to hold instream flows, in addition to governmental entities (Amos & Swenson, 2015) Water usage rights in Alaska cannot be obtained through wrongful use or possession, whether the water is appropriated or unappropriated (Estes, 2001) (Haw. Code R. § 13-169-21). Hawaii implements instream flow standards on a stream-by-stream basis based on administrative rules adopted in 1988 and 1989 (Hawaii Commission on Water Resource Management, 2023). Even though the Hawaii Instream Use Protection Act of 1982 only applied to the windward districts of Oahu and was due to expire upon the adoption of a state water code, it contained definitions and offered recommendations for the establishment of instream flow standards. A temporary instream flow standard for Windward Oahu was approved by the Board of Land and Natural Resources in 1987 in accordance with the Hawaii Instream Use Protection Act of 1982. Also, in 1987, Hawaii's Legislature passed the Water Code, which allowed the development of new temporary and long-term instream flow regulations (Sakoda, 2007).

Prior appropriation is subject to various restrictions; until a senior user uses up their entire allocation, a junior water entitlement may be curtailed or delayed. This is referred to as "water right curtailment" and is based on the availability of water. The amount of water required to fulfill the indicated usage is determined by its beneficial use. This means that if a user does not utilize their entire allotment each year for a five-year period, certain water rights may be revoked. Water rights may be affected by federal legislation like the Endangered Species Act. For instance, it could be required to limit some water rights if water use endangers the habitat of a species which is protected (UNR, 2020).

3.4 Hybrid Water Right Systems

Several states, including California and Texas, have established hybrid allocation systems that include features of both riparian and appropriative rights systems. Although there is not a single hybrid state structure that applies to all of them, they all have components for riparian and prior appropriative rights (Smolen et al., 2017; National Agricultural Law Center, n.d). California's system evolved into a special synthesis of two very distinct types of rights due to seasonal, geographic, and quantitative variations in precipitation (CSWRCB,2020). The water resource regime in California is the most complex of any western state due to the state's acknowledgment of riparian, appropriative, and prescriptive rights. This set of rights is supported by and constrained by a combination of statutory, constitutional, and common law (Boyd, 2003). There are several distinct but effective strategies for securing instream flows in California's waterways, but there isn't currently a statewide comprehensive instream flow program (CSWRCB, 2014). Through their regulatory or management authority, including the establishment and execution of regulatory environmental flow requirements, several federal, state, and local agencies in California are jointly responsible for preserving and enhancing the ecological health of California's ecosystems. Yet, traditionally, state-level initiatives or coordination of attempts at establishing balanced environmental flows have not been made. Currently, there is an active Environmental Flows Workgroup whose objective is to advance the science of ecological flows assessment and its use for supporting decision – making, intended to strike a balance between the demands on natural resources and consumptive water uses to establish environmental flows. The workgroup's objectives include supporting resource managers and the general public, addressing the need for a multi-agency, statewide approach to analyzing ecological flow needs, providing a platform for coordination and collaboration to develop connections between technical products and agency program needs (CSWRCB, n.d.). Texas, which likewise uses a hybrid water system, developed the Texas Instream Flow Program in 2001. The program studies sub-basins in the state that involves four steps: assembling and evaluating available data, developing a study design including goals, objectives, and descriptions, multidisciplinary data collection and evaluation, and integrating data to generate flow recommendations. Each step of the process is done in collaboration with stakeholders (TWDB, n.d). These states often adhere to the hybrid doctrine when it comes to water distribution. Riparian rights continue to be assigned more weight than appropriative rights under a hybrid system. When there is a drought, everyone shares the scarcity, and the priorities of riparian right holders are often equal (CSWRCB, 2020).

3.5 Types of Quantity Assignments

The World Meteorological Organization defines low flow as "water flowing in a stream during prolonged dry weather" (EPA, 2022a). Many states (see Table 2) define low flow for the purposes of establishing permit discharge limitations using design flow statistics such as the 7Q10, which is the lowest seven-day average flow that typically happens once every 10 years (EPA, 2022a). Although roughly half of the states in the country utilize the 7Q10 rule, the 7Q10 rule can either overprotect or under-protect aquatic life depending on location. For specific water quality requirements, states frequently suggest substituting hydrologically-based design flow data (in the form of xQy where x is the duration and y is the frequency). For conventional pollutants, numerous states use the 7Q2 statistic. States commonly cite different hydro-geologies to support the use of design flow other than the 7Q10 (EPA, 2022a).

Table 1. Water withdrawal allocation regulation by year

Category	***States***	***Year***	***Regulation***
Western States	Oregon	1955	Minimum streamflow protection
	Washington	1987	Minimum Water Flows and Levels Act
	California	2010	There are regional instream flow programs, e.g., "The North Coast Instream Flow Policy."
	Alaska	1980	Alaska Water Use Act
	Hawaii	1982	Instream Use Protection
NE States	Connecticut	1971	Environmental flow regulations
	Delaware	1987	Regulations Governing the Allocation of Water
	New Jersey	1990	Water Supply Allocation Permits rule
	New Hampshire	2003	Instream flow pilot standards
	Rhode Island	2004	Streamflow Working Group
	Maine	2002	Environmental flow standards
	New York	2012	Water Withdrawal Permit Program
	Massachusetts	1987	Water Management Act
SE States	Georgia	1977	Water Quality Protection Act
	Florida	2006	Minimum flows and levels
	South Carolina	2010-2011	Surface Water Withdrawal, Permitting Use, and Reporting Act
	Mississippi	2019	Water Resources; Regulation and Control
	Virginia	1989	Instream flow preservation rule
	Texas	2001	Texas Instream Flow Program

Note. For more information, please refer to the sections above. (Instream Flows-Western Origins), (Water withdrawal allocation regulation).

Table 2 of Quantity Assignments of each State

States	***Types of Quantity Assignments***
New Hampshire, Maine, Rhode Island, New Jersey, Delaware, Virginia, Mississippi, South Carolina, and Connecticut;	7Q10
Massachusetts	7Q10 and 7Q2
New York	7Q10: when assessing aquatic life protection, 30Q10: for human health protection of drinking water sources.
Georgia	By option: It allows applicants to choose between 7Q10, a site-specific flow study, or an interim-modified Tennant approach.
Texas, Oregon	Dependent on the river basin. Quantity specific to stream reach or standing body of water
California, Florida	Since they do not have a statewide regulation, the quantity types are different in different locations.
Alaska	1Q10 and 7Q10: For the protection of aquatic life, 30Q5: For the protection of human health
North Carolina	7Q10: If offstream uses are 20% or more of 7Q10, proposed withdrawals require additional analysis

3.6 Collaborating Agencies and Stakeholders

Each state has different groups of agencies that work together to develop rules and regulations governing instream flow. Typically, these agencies include the Departments of Wildlife, Fisheries, and Parks, Watershed Enhancement Board, State Water Resources Control Board, Department of Fish and Wildlife, Commission on Environmental Quality, Department of Natural Resources, Department of Health and Environmental Control, Department of Agriculture, and Commission on Environmental Quality. The Texas Instream Flow Program, for instance, was developed in 2001 by the Texas Legislature to determine how much water rivers require to sustain a healthy natural ecosystem. The Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board are the three organizations that manage the program. This program marked the first time in Texas where the public, state agencies, and academic institutions worked together on research projects to determine how much water should flow through rivers to maintain a healthy environment (TWDB, 2021).

Nearly every coastal state, including California, Texas, Oregon, Mississippi, Florida, Georgia, North Carolina, South Carolina, Virginia, Delaware, New Jersey, Connecticut, Rhode Island, Massachusetts, New Hampshire, Maine, and Hawaii, holds public hearings and encourages opinions from the public. In some places, like Mississippi, anybody whose rights would be negatively impacted by water withdrawals is required to attend a public hearing. Stakeholders are typically involved in the assessment of river systems, data collection, research design development, and evaluation of suggestions for instream flow regimes. In Texas, public and stakeholder discussions started in 2008, and four sub-basin research designs are now being developed. For water allocation, Delaware maintains a Source Water Protection Citizens Technical Advisory Committee. Prior to finalizing the surface water improvement and management plan for a priority water body in Florida, the governing board of the appropriate water management district shall hold at least one public hearing and public workshop in the region of the water body. Overall, the final updated laws must strike a cautious balance between serving community water requirements and protecting the health of water bodies. North Carolina allows for public participation at DWR informational meetings, workshops and public hearings.

3.7 Framework for Monitoring Ecological Flows

Instream flow techniques have primarily been developed by biologists and hydrologists who work for organizations with opportunities to monitor water development and control. Each state is using a different method for monitoring ecological flow (Table 3). The Ecological Limits of Hydrologic Alteration (ELOHA) and Instream Flow Incremental Methodology (IFIM) frameworks are the two most used by states (see Table 3).

ELOHA’s goal is to produce regionally significant, large-scale suggestions for environmental flow that are ecologically relevant to water managers and stakeholders. When time or resource limitations prevent comprehensive studies for all rivers in an area, the Ecological Limits of Hydrologic Alteration (ELOHA) is a novel framework for evaluating environmental flow needs in a general fashion. Building a hydrologic foundation is the first step in ELOHA. The second step is characterizing different types of rivers based on their flow patterns and geomorphic characteristics. The third step is computing the current degrees of flow alteration. The fourth step is defining flow alteration-ecological response relationships. The fifth step is using flow alteration-ecological response relationships to manage environmental flows through an informed social process (Kendy, 2009). It is important to mention that this approach may be constrained in tidal rivers and estuaries where bi-directional flows may occur.

Instream Flow Incremental Methodology (IFIM) is an incremental approach created to quantify ecological and environmental effects brought on by a specific modification in water management. The implications of a planned flow adjustment are frequently restricted to a particular stream reach since incremental approaches are generally fine-grained. However, it is usual to use incremental techniques on large, complicated networks (Bovee, 2021). Water budgets, quantitative impact analyses, minimum flow standards, and interdisciplinary analysis all played a role in how IFIM developed (Stalnaker, 1995). There are many instream flow techniques available to assess how water flow affects aquatic life, but the application of the IFIM has emerged as one of the most popular ways to define instream flow criteria (Navarro, 1994). IFIM is a set of computer-based models that determine how much fish habitat is gained or lost as stream flow alters. It is predicated on the notion that fish favor water that is a specific depth and velocity. Varied fish species and phases of development have different preferences. In its hydraulic modeling, IFIM solely makes use of the four variables depth, velocity, substrate, and cover, which are essential indicators of instream flow velocity (Pacheco, 2010).

New Hampshire uses the QPPQ (quantile translation) method (Lorenz & Ziegeweid, 2016). To determine protected instream flows on specific designated rivers and rivers reaches, the New Hampshire Department of Environmental Services (NHDES) developed regulations. Due to the dearth of stream gage data in many of those rivers, NHDES requires an accurate method for calculating daily stream flow at unmeasured sites. One such technique is HYSR's (hydrological services) QPPQ Transform. Long periods of estimated daily flows at the ungaged site are generated using known flows from an additional USGS stream gage, statistical probabilities, and nearby soil, climatic, and topography data from the watershed of the ungagged site.

The State of North Carolina has previously studied scientific approaches for environmental flows. The North Carolina Ecological Flows Science Advisory Board (EFSAB) submitted a report to the North Carolina Department of Environment and Natural Resources in 2013 that included recommendations for estimating flows to ensure riverine ecological integrity. The advisory board recommended a two-part strategy where: ecological flows would be established based on 80-90% of ambient modeled flow remaining in the stream, coupled with a critical low flow component in times of drought; and a biological-response strategy involving evaluation of ecological flows with models that connect current and future flows derived from the percentage-of-flow strategy with changes in fish and invertebrate communities (NCEFSAB, 2013). This guidance was deemed appropriate for Mountain, Piedmont and Inner Coastal Plain streams with uni-directional flows.

Table 3. Framework for Monitoring Ecological Flows by States

States	***Framework***
Washington, Oregon, California, Alaska,	IFIM
Mississippi, Virginia, Maryland, Rhode Island, Massachusetts, Maine,	ELOHA
Texas	Lyons Method (for water permitting) & Consensus Criteria for Environmental Flow Needs (for water planning)
New Jersey	Hydro ecological Integrity Assessment Process (HIP)
New York	Natural Flow Regime Method
Connecticut	Weighted evidence
New Hampshire	QPPQ

3.8 Instream Flow Considerations

Schemes for measuring instream flow are currently evolving away from single values and toward thorough river science. Instream flow hydrology and hydraulics, for instance, now consider the hydrologic regime with seasonal and inter-annual fluctuation in addition to the lowest flow value, and biological components account for aquatic and riparian ecosystems rather than simply a single target species. Considerations for water quality include temperature, dissolved oxygen, nutrient loading, and toxics, as well as in- and out-of-channel riverine physical processes such sediment dynamics and geomorphic processes. Scientists now take a larger variety of stream flow circumstances into account when addressing stream flows over this wide range of ecosystem conditions and activities, in addition to the minimum instream flow requirements (National Research Council, 2005).

3.9 Coastal Considerations

This section will look at several factors that other coastal states have utilized when deciding and establishing their instream flow programs and regulations. This material can provide guidance for potential policy-based approaches to assist with sustaining ecological integrity in North Carolina.

Coastal considerations are incorporated into certain states' ecological flow acts, primarily in eastern states. Florida rules require that when determining minimum flows and levels, consideration should be given to non-consumptive uses, natural seasonal variations in water flows or levels, and environmental values related to the ecology of the coastal, estuarine, riverine, spring, aquatic, and wetlands (Florida Statutes, 2013). The Texas Legislature established two directives to deal with the issue of the need to protect environmental flows that may result in increased water demands that might restrict or modify flows, potentially resulting in the degradation of aquatic and coastal ecosystems (TWDB, n.d). Coastal consideration in Texas is reliant on the unique basin-bay system of Texas. To the greatest extent possible, coastal uses and resources in Maine adhere to the enforceable rules of the state's Coastal Management Program. The North Carolina EFSAB recommended that ecological flow approaches should consider anadromous fish habitat conditions, downstream salinity, and overbank flow for intertidal watersheds (NCEFSAB, 2013).

3.10 Interstate Collaborations

Some states that share water borders have agreements in place to protect flows. The Delaware River Basin Commission (whose members hail from Delaware, New Jersey, New York, Pennsylvania, the federal government, and the cities of New York City and Philadelphia) has a subcommittee on ecological flows that provide scientifically based information and recommendations (Delaware River Basin Commission, 2023).

Another example of interstate water collaboration is the Apalachicola-Chattahoochee-Flint Basin Commission (ACF Basin Commission), which is now established as an interstate administrative body with authority to develop and amend a formula for allocating the surface waters of the ACF Basin among the states of Alabama, Florida, and Georgia (Corn, 2008) who are engaged in a "tri-state water war" over the limited water supplies in the Chattahoochee, Flint, and Coosa Rivers (Smolen et al., 2017). Apalachicola-Chattahoochee-Flint (ACF) river system water allocation has been a source of ongoing interstate conflict between Alabama, Florida, and Georgia (Corn, 2008). The drawdown of Lake Lanier in the fall of 2007 to support minimum flows in the lower basin's Apalachicola River ramped up the conflict between these states, and the conflict has persisted to the present day (Manganiello, 2021). This situation created the rationale for the minimum flow requirements. The sustainability of river flows to fulfill civic, power, and environmental demands is a problem for lower basin stakeholders, who also doubt the effectiveness of Georgia's municipal, industrial, and agricultural water conservation programs (Corn, 2008).

Commissioners who represent the federal government, the states of Maryland, Pennsylvania, Virginia, and West Virginia, and the District of Columbia compose the Interstate Commission on the Potomac River Basin (ICPRB), which was established by an act of Congress in 1940 through an interstate compact. Through regional and interstate collaboration, the ICPRB aims to improve, protect, and preserve the water and related land resources of the Potomac River basin and its tributaries. The Commission was established with the main purpose of offering technical assistance and knowledge to the watershed jurisdictions and providing aid in the five watershed jurisdictions' efforts to conserve and restore environmental flows (Interstate Commission on the Potomac River Basin, 2022; Bencala, 2022). The interstate compacts also include emergency rules to ensure ecological flows. The 1982 agreement between the federal government, the Fairfax County Water Authority, the Washington Suburban Sanitary Commission, the District of Columbia, and the ICPRB is the foundation for the Virginia Water Protection (VWP) permit for surface water withdrawals in Virginia. When the restriction or emergency stage is proclaimed in the Washington Metropolitan Area pursuant to the terms of the Potomac River Low Flow Allocation Agreement or when the operating guidelines specified by the Drought-Related Operations Manual for the Washington Metropolitan Area are in effect, VWP permits issued for surface water withdrawals from the Potomac River between the Shenandoah River confluence and Little Falls must contain a condition that requires the permittee to reduce withdrawals. The department will instruct the permittee as to when, by how much, and for how long withdrawals should be decreased after consulting with the Section for Cooperative Water Supply Operations on the Potomac (CO-OP) (US Code, Code of Virginia, 2022).

3.11 Seasonal Differences in Regulations

Instream flow levels are not fixed for the entire year. Since streams naturally experience seasonal variations and different types and life stages of fish have varying needs, instream flows are adjusted at various levels throughout the year. Natural stream flow can vary significantly from year to year, often by a factor of ten, on any particular day (Washington State Department of Ecology, 2017). Several states consider the realities of variable instream flow levels with their regulations. In Georgia, for instance, depending on fish and wildlife life stages, instream flow needs are specified in month or half-month intervals. 30/60/40% Mean Annual Flow (Water Supply Reservoir): If a reservoir is proposed, the applicant must always release from the reservoir the lesser of the following amounts: 30% of the mean annual flow or inflow from July through November; 60% of the mean annual flow or inflow from January through April; and 40% of the mean annual flow or inflow from May, June, and December. For surface water withdrawers, the flow in South Carolina is set at 40% of the mean annual daily flow for the months of January, February, March, and April; 30% of the mean annual daily flow for the months of May, June, and December; and 20% of the mean annual daily flow for the months of July through November. New York uses monthly flow-duration information to apply monthly differences. In Rhode Island, variations depend on fish life stages and hydroperiods. The monthly median flow figures are applied in Massachusetts. Depending on the season, laws differ in Oregon, Maine, Maryland, Hawaii, California, Florida, and Connecticut, among other places. The criteria in Maine, for instance, provide a quantitative criterion for how much water can be withdrawn when flows or water levels exceed a predetermined seasonal threshold amount. A habitat approach or a hydrologic approach are the two methods used to determine seasonal thresholds (Nature Conservancy, n.d). In Oregon, the Water Resources Department establishes a monthly 80 percent exceedance flow for gaged water sources based on measured mean daily flows for that month throughout the time on record. The Department calculates exceedance flows for a common base period to account for flow fluctuations from wet to dry seasons (Amos, 2009).

3.12 Nonseasonal Flexible Allocation Mechanisms (Drought)

Most coastal states with stream flow regulations have a threshold and take flexibility in the laws into consideration when a drought occurs. Some states, like Maine, use a variance that is authorized and determined by the rule using the Palmer Drought Index, the most used index for drought in the country. In this instance, extraction stops without providing any form of exception to other users when flows and water levels fall below the seasonal flow or water level threshold (Nature Conservancy, n.d). Others, like Rhode Island, encourage freshwater wetlands and buffers in accordance with its Water Act. Freshwater wetlands and buffers supply and sustain surface and groundwater supplies by serving as recharge or discharge areas and, in the case of certain ponds, as surface water reservoirs. These freshwater wetlands and buffers, either individually or collectively, are a significant factor in replenishing ground and surface water supplies, maintaining stream flows, transporting surface waters, and storing and distributing surface waters and groundwater during dry seasons, even though groundwater recharge and discharge functions and values may vary seasonally (RI Code of Rules 250-RICR-150-15-2.2, 2022).

In Florida, Virginia, and Georgia, minimum flows and levels must be protected during the declaration of a water shortage unless the drought is so severe that doing so would endanger public health and safety or, in other cases, go against the public interest as assessed by the governing board. In this case, some states permit additional withdrawal, and some reserve the right to divide the remaining surface waters equally between the environment and public health and safety under these severe multi-year droughts or other emergencies (U.S.C, § 62.1-44.15:22, 2021). In times of drought, Delaware adopts a modified Tidal Capture Structure (TCS) operation plan to increase the capacity of the water supply during a drought (Kauffman, 2002). When drought occurs in Washington, Oregon, and other appropriation states, older (senior) water right holders have priority over younger (junior) water right holders and are entitled to the entire quantity of their water right. Examples of permit requirements that may be used in New York include restrictions on the rate or rate of change (ramping) of regulated withdrawals, stepped restrictions based on flow conditions, contingency measures for limiting water withdrawals during seasonal or drought shortages, the establishment of pass by flows or conservation releases, monitoring and reporting requirements, and more. The North Carolina EFSAB recommended a critical low flow component within the percentage-of-flow strategy to ensure that increases in the magnitude and duration of extreme low flows during drought conditions are minimized (NCEFSAB, 2013).

3.13 Water Quality (Biology, Salinity, Sediments)

Nearly all the coastal states with stream flow regulations have taken water quality into account. Additionally, nearly all coastal states that have stream flow regulations have taken the lives of fish and other species into account. Their regulations state that the biological properties of surface waters shall not alter because of their water withdrawal rules. For instance, in Rhode Island, the state considers the reality that not all watersheds have the same biological value because of watershed characteristics and current human influences that may change the characteristics of the habitat and/or natural streamflow within a watershed. The capacity of the stream to assimilate contaminants is being negatively impacted by additions to or diversions of stream flows, which has an adverse effect on existing instream uses or public health. To protect the aquatic ecosystem, it is not enough to maintain the natural streamflow. What kinds of species can live in the stream will also depend on how the water quality, temperature, and sedimentation vary from the expected ranges. As an illustration of this protection, the Washington Department of Ecology regulates instream flows at levels that are regularly met to enhance fish populations. To maintain robust fish populations and survival through low water years, the state's native fish species depend on the added boost they receive from "excellent water years." Stream flows enhance the picturesque and aesthetic features of natural environments in addition to providing habitat for fish and wildlife. They also support recreation, stock watering, and other water-related purposes. In general, maintaining instream flow levels that are sufficient for fish promotes other instream resources and values, such as water quality and animal habitat (Christensen, 2017). The Policy for Maintaining Instream Flows in Northern California Coastal Streams (Policy) establishes principles and guidelines for maintaining instream flows for the preservation of fishery resources while minimizing the effects of water supply on other beneficial uses of water, such as irrigation, municipal use, and domestic use. For certain rivers or streams, the Policy does not specify any instream flow criteria. No specific water diversion projects are approved by the Policy, nor does it outline the criteria that will be included in the water right permits, licenses, or registrations. As an alternative, the Policy lays out standards for assessing the possible effects of water diversion projects on stream hydrology and biological resources (Instream Flows Policy, 2014).

Stream biologists have understood the importance of strong flows or freshets for fish migration, both adult and juvenile for many years (Wald, 2009). Instream flows are advised by the Washington Department of Fish and Wildlife (WDFW) for the administration of water rights, mitigation of major project development and operations, and the preservation of endangered species. Both relatively low chronic flows required for fish and wildlife survival and shorter duration high flows required for maintaining and building their habitat are considered instream flows. Maintaining the quality of the water, which includes its temperature, dissolved oxygen content, and impurity concentration is another crucial aspect. River/river basin factors are important in Texas as well (T. I. F, 2008). Abundance and relative frequency of native species, different fish species, benthic species, habitat quality for important species, diversity and size of microhabitats, vegetation (distribution, richness, and diversity), soil types, and hydrology are all considered (T. I. F, 2008).

Some states apply methodologies and rules that are specific for fish and animals, reducing pollution, and other water quality issues. Although there are biological concerns, the concepts and recommendations in the California policy might not apply in situations where they would conflict with increased flow needs for other instream biological resources. Massachusetts has established a thorough analysis of the possible effects of the withdrawal needed in terms of public drinking water supplies, water quality, wastewater treatment, waste assimilation, groundwater recharge areas, navigation, hydropower resources, water-based recreation, wetland resource areas, fish and wildlife, agriculture, floodplains, and other withdrawal points (310 CMR 36.00, 2014).

Only a few of the coastal states take salinity into account. In Hawaii, the state government identifies the regions of the state where freshwater resources are at risk from saltwater intrusion, and they inform the public, the appropriate county mayor, and the council of their findings (HI Rev Stat § 174C-5, 2019). Several states, including California, Texas, Florida, Georgia, Virginia, and New Jersey, take water salinity into account when enacting legislation. Based on already published research and data, the Florida initiative contains salinity envelopes and freshwater inflow targets for the estuaries (Florida Statutes, 2022). The Florida initiative accounts for how water inflows are under the control and jurisdiction of water management districts and attempts to reduce the frequency and length of undesirable salinity ranges while addressing other water-related needs of the region, including water supply and flood prevention.

3.14 Instream Flows Policy Discussion

The protection of instream flows is a complicated issue that involves many parties, research, and policy. States that offer varying degrees of functional instream flow protection for their rivers, lakes, wetlands, and aquifers employ a wide variety of terms, tactics, and program structures (SARP, n.d). Most instream flow effects are more apparent during times of low flow. When streams have already reached low levels, the demand for water is typically at its peak. The need for power and for irrigating lawns, crops, and golf courses increases as the weather gets drier and typically hotter (NCDEQ, n.d). The North Carolina Division of Water Resources will have to balance all of those needs if designing ecological flow criteria. Currently, as stated earlier, the Water Use Act of 1967 is the only statute that directly regulates withdrawal, and the statute only applies to capacity use areas. Therefore, the North Carolina Division of Water Resources can only make recommendations outside of these boundaries.

Many states in the eastern United States have regulated riparian water legislation and can establish permit restrictions for withdrawals under their water allocation schemes (SARP, n.d). The riparian rights notion serves as the foundation for North Carolina's water legislation (NCDEQ, n.d). Most states include their ecological flow regulations under their water withdrawal allocation permit. Also, water allocation permits should take both surface and groundwater resources into consideration since they are interconnected.

The conditions and experiences of other states can be utilized to generate the most appropriate recommendations for North Carolina streams in terms of technique and water threshold. Aquatic life, for instance, is one of the key factors in instream flow regulations, which are essential in North Carolina as well. Native species must be able to move both inside a river and into nearby flooded regions since they are uniquely suited to each river's natural flow patterns. The habitat and life-stage signals necessary to sustain a healthy aquatic system are formed by seasonal and annual fluctuations in the magnitude, frequency, and timing of both major and minor flow events (SARP, n.d). Also, when establishing the state's instream flow policy goals and program objectives, the costs and values of protection should be taken into consideration (SARP, n.d). Even while each state's environmental flow protection laws have the same basic structure, by understanding more about them, we may better grasp the subtle variations that exist between each state's laws. A more thorough and comprehensive regulation for instream flow is established in some states, including Florida, Texas, and Washington, in combination with revised environmental flow protection legislation. Even while not all states factor in every possible parameter that can have an impact on the environmental flow, considering the various factors described in this study could help the state establish guidelines and also be utilized to enhance already-existing legislation and management.

4. Previous Coastal Ecological Flow Efforts in North Carolina

During the deliberations of the EFSAB, it became evident that all monitoring and modeling efforts were directed to gaged or gageable reaches of rivers for reasons discussed above. This excluded much of the watershed area of North Carolina in the Coastal Plain. To address this region, a Coastal Ecological Flows Working Group (CEFWG) was formed, which became responsible for Appendix C of the report of the NCEFSAB (2013). The group provided a framework for how ecological flows in the Coastal Plain could be approached but had limited time and resources to evaluate this framework. The efforts of the APNEP Flows Working Group, its phase 1 project (O'Driscoll et al. 2018) and this project are extensions and enhancements of their work.

The framework for Coastal Plain ecological flows was developed as three steps: a geomorphic typology of Coastal Plain waterways, identification of ecological assemblages that might be used as indicators for low ecological flows for each geomorphic class, and ecological flows determinant that could affect assemblages within each geomorphic class. The following is a brief summary of the group's efforts.

As coastal rivers are found closer to estuaries, the lower elevations, gentle slopes and influences of both astronomical and wind-driven tides disconnect the link between flow and stage. The changes are expressed in the habitats of stream reaches. These interactions are represented in the geomorphic typology as seen in Figure 1.

Origin and slope were used, then, to help separate the kinds of assemblages that could be appropriate for use as ecological flow indicators. The Piedmont and Upper (also referred to as Inner) Coastal Plain rivers with medium to steep gradients were largely included in the EFSAB recommendations. Resident fish and macroinvertebrates were used as ecological indicators. As the group considered the Coastal Plain, the decision was made to focus on fish. Macroinvertebrate indices from the Piedmont tend to be less relevant in the Lower (also referred to as Outer) Coastal Plain (NCEFSAB 2013). Further, fish assemblages were divided into anadromous and estuarine resident fish. Freshwater fish communities were not considered directly. Wetland vegetation was included as another indicator assemblage in the Coastal Plain. Riparian forests, swamps and marshes are inextricably linked to river flows and water quality (Herbert et al. 2015). Thus, they are subject to alteration resulting from flow conditions, especially extended low flows.

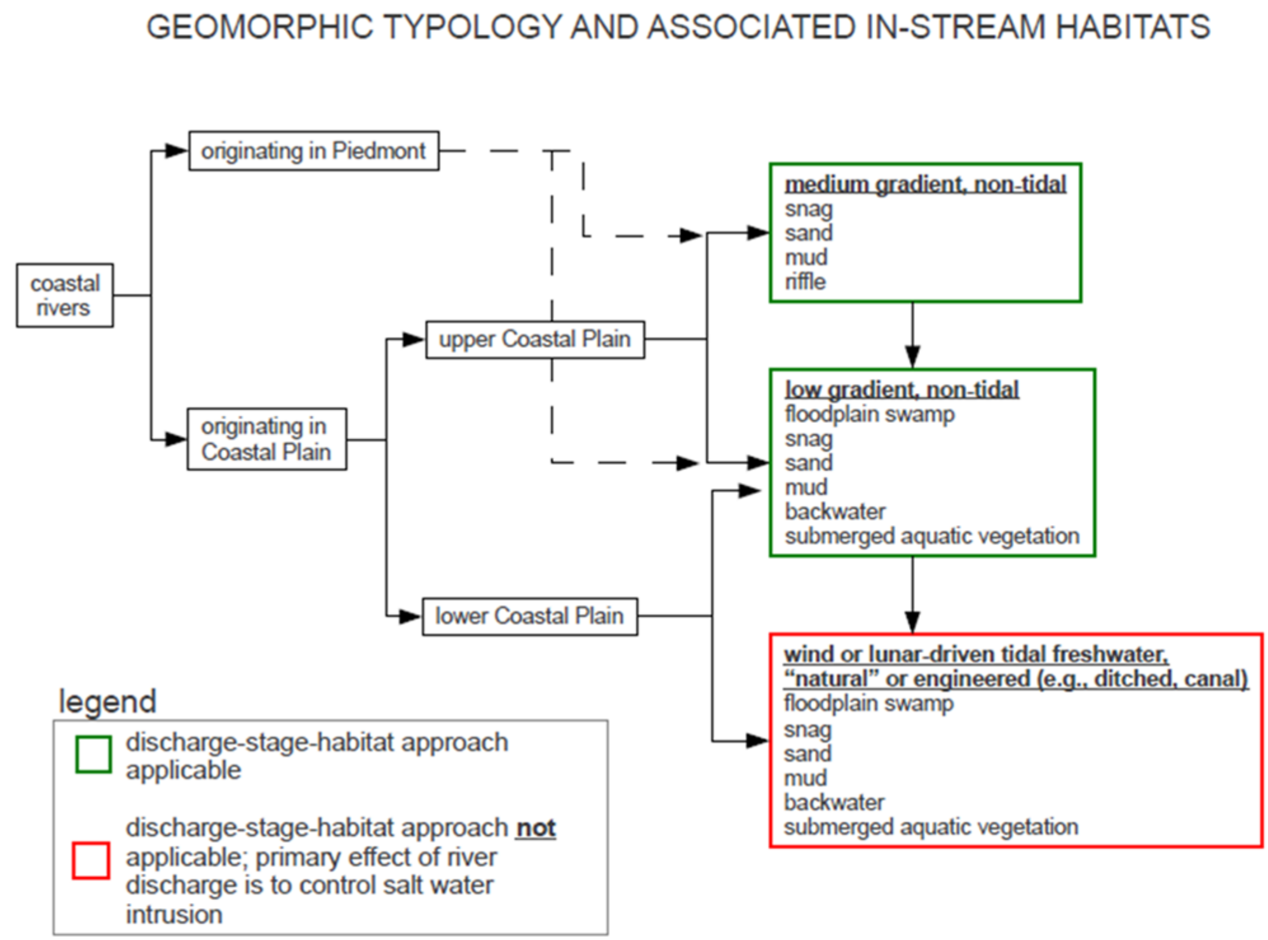


Figure 1. Typology of coastal streams proposed for Coastal Ecological Flow approach decision making. (Appendix C of NCEFSAB 2013).

Table 4. Link between waterway category and key assemblage that could be used for ecological flow assessment. (Appendix C of NCEFSAB 2013)

Origin	Slope	Assemblage		
		Anadromous Fish	Resident fish	Vegetation (Foundation species)
Piedmont	Medium gradient	X		
Upper Coastal Plain	Medium gradient	X		
Upper Coastal Plain	Low gradient	X		X
Lower Coastal Plain	Low gradient	X		X
Lower Coastal Plain	Wind or tidal driven flow		X	X

Finally, the group addressed factors that could affect the indicator assemblages as divided by river origin and slope. It was recommended that some extension of the EFSAB determinants and protocols be used on medium gradient streams independent of origin as these streams should be expected to have a reasonable flow/stage relationship. Assemblages within low gradient and wind and tidally driven systems were expected to be affected by habitat size (both related to depth and horizontal extent) and condition associated with flow and overbanking. All streams within the Lower Coastal Plain were considered to be subject to intrusion by salinity. In turn salinity would have effects on ecological assemblages. As will be seen, we have focused much of our attention on the upstream intrusion of salinity and its potential influences on assemblages.

Table 5. Categories of waterways within the Coastal Plain and relevant ecological flow (EF) determinants. (Appendix C of NCEFSAB 2013)

Origin	Slope	EF determinant			
		EFSAB extension	Discharge & Habitat	Downstream Salinity	Overbank Flow
Piedmont	Medium gradient	X	X	X	
Coastal Plain	Medium gradient	X	X	X	
Coastal Plain	Low gradient		X	X	X
Coastal Plain	Wind or tidal driven flow			X	X

Further work based on the Coastal Ecological Flows Working Group (NC DEQ 2013) recommendations is documented in O'Driscoll et al. (2018). This report focused on the status of available flow and ecological flow-related data for the Albemarle-Pamlico drainage basin. This study recommended further work on evaluating watershed-scale water use (particularly during summer low flow periods), additional flow and water quality monitoring along tidal reaches, cooperative efforts to develop a watershed-scale ecological flow program, stakeholder involvement, and pilot studies in select coastal watersheds in the Albemarle-Pamlico drainage basin (the Executive Summary is included in Appendix A).

5. Recent Understanding of Coastal Ecological Flows

At the time of the earlier ecological flow efforts by NC (NC DEQ 2013) there was limited guidance for coastal systems. More recently, ecological flows efforts for estuaries have been synthesized and there is a growing body of literature as summarized by Chilton et al. (2021) and Montagna (2021). Both provided reviews of the consequences of flow variation and ecological flow requirements for estuaries. Rivers within the Lower Coastal Plain were not directly included. Although it is known that freshwater flows play a major role in estuarine processes and ecosystem health, the freshwater flow requirements for estuaries or tidal reaches of rivers are not as well developed as with rivers upstream. Their reviews indicated that permanent decreases in low flows and/or increases in the frequency and magnitude of drought can lead to a wide range of impacts to estuarine ecosystem processes including: reduced delivery of organic matter, sediments, and nutrients; habitat losses; reduced sediment scour; increased salinity; increased residence time; increased likelihood of phytoplankton blooms; declines in dissolved oxygen; and associated declines in water and sediment quality. Chilton et al. (2021) concluded that approaches to develop ecological flow requirements for estuarine systems should include long-term flow, water quality, and ecological data collection and modeling efforts, the characterization of acceptable states, an understanding of stakeholders and management tradeoffs, and holistic watershed management. These approaches were largely supported by Montagna (2021). They are needed for adaptive management of estuarine watersheds because maintenance and re-establishment of natural flow regimes are critical to healthy estuarine and coastal riverine ecosystems.

We will highlight the importance of the connectivity of reaches of tributary rivers with downstream estuaries. In fact, downstream connectivity is far more important in these reaches than for farther upstream. Also, the reduced elevation gradient in the North Carolina Coastal Plain compared to many other estuarine watersheds may also influence low flow dynamics in ways that differ from those described elsewhere in the reviews of Chilton et al. (2021) and Montagna (2021). Generalizing ecological flow requirements across diverse estuaries and coastal river systems can be difficult, because of the diverse characteristics of estuaries and the watersheds that drain to them and the stakeholders involved. Few of these systems have been studied with ecological flows in mind. Therefore, there is a growing need to evaluate ecological flow requirements for estuaries and the coastal rivers that feed them. As a first step, we initiated a pilot project on the Trent River watershed in Jones and Craven Counties, North Carolina.

6. Trent River Pilot Study as an Exemplar for APES Coastal Rivers

The Trent River Pilot Study was initiated to develop guidance on determining ecological flows (with a focus on low flow aspects) in Coastal Plain waterways where established ecological flow methods are limited. An interdisciplinary approach was used to: evaluate low flows and their potential influence on water levels and water quality; improve understanding of flow-salinity dynamics in the riverine-estuarine transition zone; evaluate effects of low flows and increased salinity on wetland habitat and fish communities; estimate the influence of water use on low flows; and assess stakeholder perceptions and preferences regarding potential policy actions.

6.1 Study Area

The Albemarle-Pamlico Estuary System (APES) is the second largest estuarine system in the United States and drains six of the major river basins in North Carolina including the Chowan, Neuse, Pasquotank, Roanoke, Tar-Pamlico, and White Oak River Basins (Fig. 2). The gradient for each of these rivers ranged from 0.07 – 0.51 m/km (0.35 – 2.7 ft/mi), and rivers whose headwaters originated within the Piedmont typically had larger gradients (Table 6). The natural headwaters for both the Neuse and Roanoke Rivers extend farther upstream but both rivers were dammed at Falls Lake and Roanoke Rapids Lake, respectively. The Chowan River forms at the confluence of the Nottoway and Blackwater Rivers, which are major rivers draining southern Virginia. The APES drains both NC and VA consisting of a total area of approximately 95,300 km^2 (~59,000 mi^2). The APES consists of >265,000 natural and artificial drainage features that extend a total distance of approximately 120,000 km (~75,000 mi) (Table 7). About 60% of the drainage features in the APES are intermittent or perennial streams/rivers and collectively account for >70% of the total distance. Hydrographical features drain several physiographical provinces including the Valley and Ridge and Blue Ridge provinces in western VA to the Piedmont underlying central NC and VA finally to the Coastal Plain of eastern NC and VA. In addition to the six major rivers that feed the APES, there are a multitudinous number of streams that either directly drain to the APES or are tributaries of the six major rivers. The current study focused on assessing ecological flows within the Trent River, which is within the Lower Neuse River Basin. The Neuse River Basin drains an area of 15,701 km^2 (6062 mi^2) across 19 counties in NC and is completely contained within the state. The basin consists of approximately 58,000 linear flowlines representing natural or artificial drainage features that extend >23,000 km (~15,000 mi) in total length (Table 8). The headwaters of the Neuse River originate in the Piedmont of North Carolina and flows to the southeast before draining into the Neuse Estuary that flows into the Pamlico Sound. The Neuse River Basin can be further subdivided into four sub-basins (i.e., 8-digit hydrologic unit code), including the Upper Neuse River, Contentnea, Middle Neuse, and Lower Neuse River Basins. The Trent River Watershed drains the western half of the Lower Neuse River Basin.

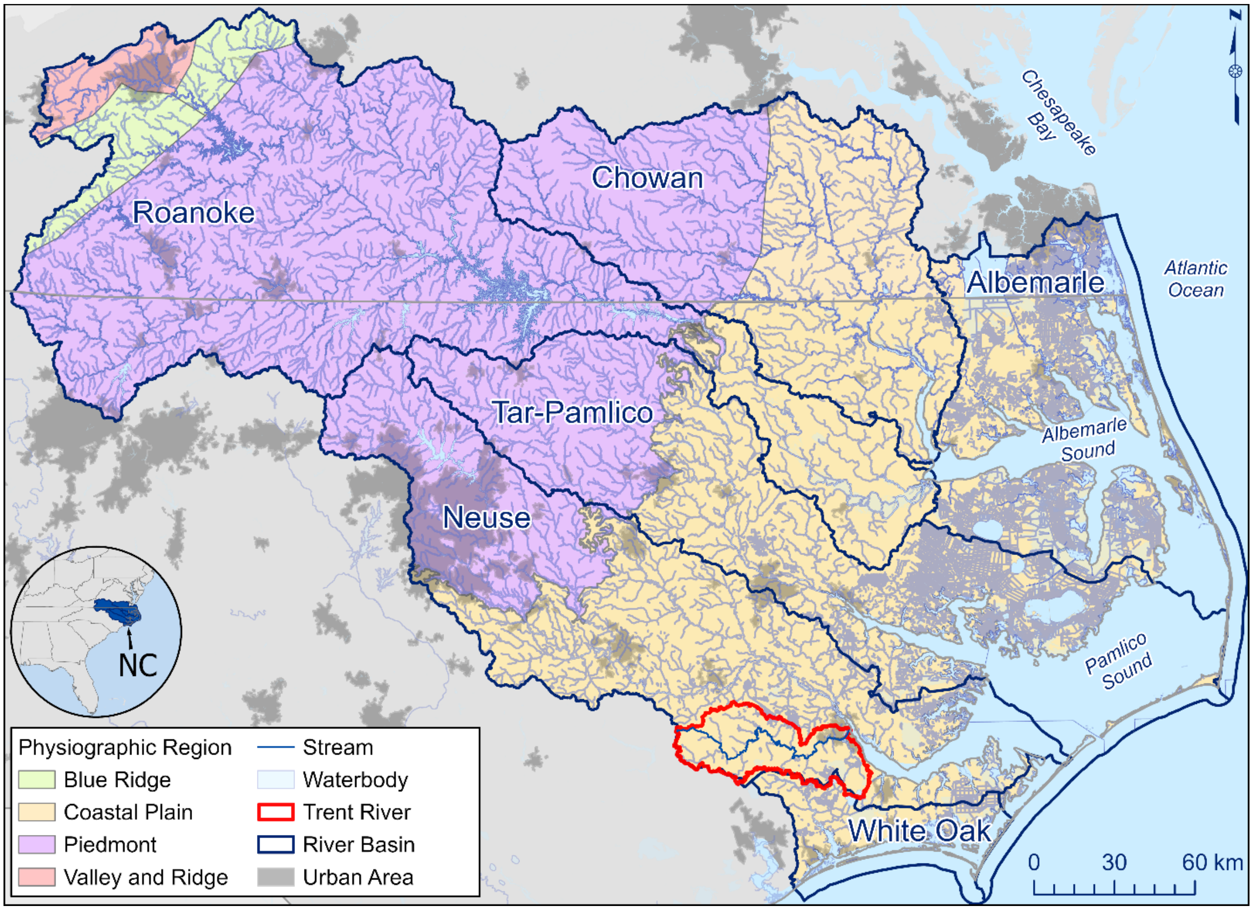


Figure 2. Map of the Albemarle-Pamlico Estuarine System depicting its six major river basins, hydrographical drainage features, physiographic provinces, and urban areas. The Trent River Sub-watershed is also shown in red.

Table 6. Stream gradient for the major rivers that drain to the Albemarle-Pamlico Estuary System.

River	Headwater Province	Elevation Difference		Total Length		Stream Gradient	
		(m)	*(ft)*	*(km)*	*(mi)*	*(m/km)*	*(ft/mi)*
Chowan[1]	Coastal Plain	5.49	18	83.24	51.73	0.066	0.348
Neuse[2]	Piedmont	66.75	219	380.19	236.24	0.176	0.927
Pasquotank	Coastal Plain	5.79	19	70.86	44.03	0.082	0.432
Roanoke[2]	Piedmont	42.37	139	211.53	131.44	0.200	1.058
Tar-Pamlico	Piedmont	195.68	642	382.39	237.60	0.512	2.702
White Oak[3]	Coastal Plain	9.75	32	71.06	44.16	0.137	0.725

[1]= Chowan forms at the confluence of the Nottoway and Blackwater River at the NC-VA border; gradient only includes the NC portion of the stream.
[2]= Stream dammed; gradient measured from the discharge of dam to river mouth.
[3]= White Oak River begins at the confluence of the North and South Prongs; gradient measured from this point to the Bear Island Inlet

Table 7. Total number and distance of natural and artificial features draining the Albemarle-Pamlico Estuarine System.

Flowline Type	Total Features (#)	Total Distance (km)	Total Distance (mi)
Artificial Pathway	66,292	15,314	9,516
Canal Ditch	43,126	18,083	11,236
Connector	575	789	49
Drainageway[1]	1	0	0
Pipeline	36	32	20
Aqueduct, at/near surface	5	9	6
Aqueduct, underground	2	1.5	0.9
General, underground	29	21	13
Stream/River	155,754	85,740	53,276
Intermittent	88,643	53,730	33,386
Perennial	67,107	32,009	19,889
Total	***265,784***	***119,247***	***74,097***

[1]= Feature identified, but not mapped thus distance could not be quantified.

Table 8. Total number and distance of natural and artificial features draining the Neuse River Basin.

Flowline Type	Total Features (#)	Total Distance	
		(km)	(mi)
Artificial Pathway	16,034	3290	2,044
Canal Ditch	7,270	2998	1,863
Connector	163	25.54	15.87
Streams/Rivers	34,525	17166	10,667
Intermittent	21,199	11183	6,949
Perennial	13,324	5983	3,718
Total	***57,992***	***23479***	***14,589***

The Trent River Watershed drains an area of approximately 1421 km^2 (~549 mi^2) within the Lower Neuse River Basin (Fig. 3). The river predominantly flows from west to east with a total stream length of approximately 141 km (~88 mi). The headwaters of the Trent River originate north of Pink Hill, NC and west of Lawsons Mill, NC. The Trent River terminates at its confluence with the Neuse River near New Bern, NC. The Trent River Sub-watershed consists of approximately 3,200 natural and artificial drainage features, nearly 70% of which consist of intermittently or perennially flowing streams or rivers (Table 10). Collectively, these hydrographical units travel approximately 1,600 km (~1,000 mi), and streams/rivers comprise nearly 75% of the total distance.

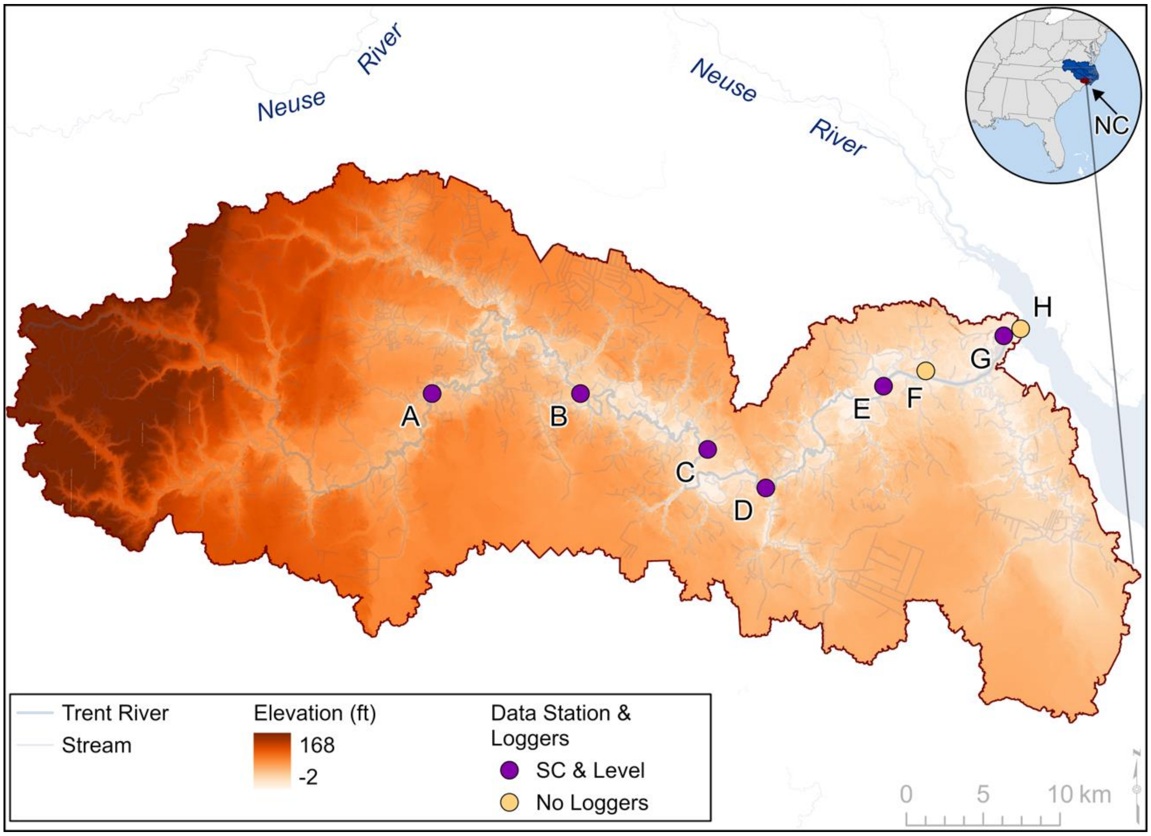


Figure 3. Elevation and sampling site map of the Trent River watershed. A legend for each station is available in Table 9. USGS stream discharge and stage monitoring stations are at sites A (near Trenton) and D (Pollocksville).

Table 9. List of data collection stations where loggers and/or secondary data from other sources was compiled.

Site	Site ID	NCDEQ Site	USGS Stations	Loggers	Coordinates
Near Trenton	A	J8690000	Near Trenton	SC, Lvl	35.065157; -77.456898
Trenton Boat Ramp	B			SC, Lvl	35.065202; -77.350973
Oak Grove	C			SC, Lvl	35.032514; -77.260209
Pollocksville	D	J8730000	Pollocksville	SC, Lvl	35.009918; -77.218826
River Bend	E			SC, Lvl	35.069346; -77.134658
Trent Woods Dr	F	J8770000			35.078217; -77.104361
Lawson Creek Park	G			SC, Lvl	35.09869; -77.048825
New Bern	H	J8570000			35.102837; -77.03665

Table 10. Total number and distance of natural and artificial features draining the Trent River Sub-watershed.

Flowline Type	Total Features (#)	Total Distance (km)	(mi)
Artificial			
Pathway	580	201.66	125.31
Canal Ditch	415	233.81	145.28
Connector	12	0.72	0.45
Stream/River	2,192	1182.49	734.76
Intermittent	1,241	688.53	427.83
Perennial	951	493.96	306.93
Total	***3,199***	***1618.68***	***1,005.80***

6.2 Methods

A geographic information system (GIS) database was developed using ArcGIS Pro (Environmental Systems Research Institute [ESRI], Redlands, CA, USA) to generate cartographical products, visualize data, and analyze spatial patterns in water quality and quantity data. The map of the APES was developed by integrating publicly available data into the GIS to depict physiographic provinces (NC DEQ, 2018; USGS, 2021), river basin boundaries (USGS, 2023a), hydrographical features (USGS, 2023a), and urban areas (US Census, 2020). The Trent River Sub-watershed was visualized using the same data sources in addition to *StreamStats 4.0* (USGS, 2023b) to delineate the sub-watershed boundary. Land cover data were compiled from the 2019 National Land Cover Database (MRLC, 2023) to classify and characterize land cover in the Trent River Sub-watershed. The National Wetlands Inventory (US FWS, 2023) data were integrated into the GIS database. These data were included to characterize wetland type based on salinity tolerance (e.g., freshwater, estuarine, and marine). In addition to GIS data to characterize land cover, additional data were compiled to characterize human-driven factors in availability of water within the Neuse River Basin and Trent River Sub-watershed. Sources of groundwater and surface water for public water use were included in the GIS database to identify locations where water withdrawals occur (NC OneMap, 2022) (Appendix B). Additionally, water treatment plants, wastewater treatment plants, and non-discharging facilities were integrated into the GIS dataset to identify locations where facilities dispose of treated wastewater from water purification or wastewater treatment processes.

Elevation was calculated for the Trent River Sub-watershed by creating a digital elevation model. The model was created using quality level 2, light detection and ranging (QL2 LiDAR) data accessed from North Carolina Emergency Management (NCEM, 2023). The QL2 LiDAR dataset consists of raster files using 5, 10, 20, or 50 ft grids. The 5-ft grid was used for this digital elevation model to maximize resolution and provide more accurate derivations in estimating elevation from the LiDAR dataset. After compiling the LiDAR data, the raster layer was clipped using the Trent River Sub-watershed boundary to assess elevation differences throughout the sub-watershed. An elevation profile for the Trent River was constructed using elevation data extracted from the digital elevation model at data collection sites. Three longitudinal surveys were conducted along the Trent River to collect specific conductance readings. The surveys took place on 13 November 2021, 8 March 2022, and 24 June 2022. Specific conductance was used to develop an inverse distance weighting model to interpolate specific conductance values between measurement points along the river. Salinity (ppt) was estimated by multiplying specific conductance (mS cm^{-1}) at 25°C by a factor of 0.493. These data were compared to vegetative surveys and wetlands data to determine if increased salinity corresponded with changes in salt tolerant plants and/or wetland types classified by US FWS (2023).

To evaluate longer-term salinity variations in the Trent watershed, we utilized NC DEQ ambient monitoring data collected at Trent River ambient monitoring stations between 1996-2019. Those locations, from upstream to downstream are near Trenton (adjacent to USGS stage gage), Pollocksville (adjacent to USGS stage gage), Trent Woods, and New Bern (Figure 3). In addition, specific conductivity and water level loggers were installed during the summer of 2021 to augment the USGS and NCDEQ data. Loggers were installed at: the USGS gages near Trenton and Pollocksville, the Trenton boat ramp, Oak Grove Rd., River Bend, and Lawson Creek Park (New Bern) (Figure 3), with data collected at 15-minute intervals.

6.3 Flow and Salinity Considerations

River flow is a "master variable" for maintaining aquatic ecosystems. Low flows occur naturally during dry periods and/or periods when evapotranspiration exceeds rainfall inputs (typically in summer – early fall months in eastern North Carolina). Low flows are typically sustained by groundwater inputs (baseflow) that help maintain habitat availability, water temperature, water quality, and the connectivity with riparian vegetation and wetlands (Postel and Richter 2003). Low flows play an important role in maintaining ecological integrity in aquatic systems because of their influence on contaminant dilution, saltwater intrusion, and the quality and quantity of aquatic habitat (Price et al. 2011). The natural factors which influence the low flow regime of a stream include topography, vegetation, soils and lithology, and regional hydroclimatology (Ledford et al. 2020). The anthropogenic factors which can influence low flows include water use, changes in vegetation (cutting, deforestation, or planting), wastewater effluent discharges and irrigation return flows, inter-basin transfers (both wastewater and water), dams and regulation of flow regime, and climate change (O'Driscoll et al. 2010, Ledford et al. 2020). Low flows can be vulnerable to land use change, climate change, and water withdrawals. Although the timing, duration, and range of streamflows are all important for ecological flows, the low flow component of the hydrography is most likely to be affected by water withdrawals when compared to high flows and floods (Rolls et al. 2012).

Through a synthesis of global literature, Rolls et al. (2012) evaluated the ecological responses to low flows in riverine ecosystems. They proposed four principal effects:

1. Low flows reduce the extent of physical aquatic habitat (depth, area, volume, velocity). These changes can reduce the density and diversity of biota. For example, decreased depth can reduce or

prevent passage of diadromous fishes. Flow velocity can affect species composition since different organisms inhabit lotic and lentic systems. A reduction in water volume under low flow conditions would likely modulate a variety of ecological processes, such as predator-prey interactions and interspecific competition.

2. Low flows mediate changes in habitat conditions and water quality (increased dissolved oxygen range, maximum temperature, temperature range, conductivity, decreased minimum and mean dissolved oxygen). Due to water quality tolerances, these changes can alter diversity and distribution of biota.

3. Low flows affect sources and exchange of material (e.g., nutrients, organic matter, sediment supply) and energy in riverine ecosystems (loss of longitudinal, lateral, and vertical connections). These changes can reduce the rates of energy transport within the food web, which may limit ecosystem productivity.

4.Low flows restrict connectivity and diversity of habitat (increased disconnection between habitat patches and river reaches). These changes can alter the diversity of biota.

Although these general effects are supported by numerous studies, Rolls et al. (2012) noted a lack of studies specifically isolating the effects of low flows on changes in ecosystem structure and function due in part to the short-term nature of many studies. In addition, although ecological responses may be notable for longer term low flow changes (e.g., changes in flow regime from perennial to intermittent), less information is available to evaluate the ecological responses to short term low flow events.

The long-term flow record at the Trent River near Trenton USGS station provides data from 1951-present. Earlier analysis by Weaver (2015) indicated that low flows (measured as 7Q10) declined by approximately 29% from 1998 (1.4 cfs) to 2011 (1.0 cfs). As previously mentioned, the 7Q10 is the 7-day low flow average that has a 10-year recurrence interval and is used as a metric for evaluating low flows at stations with longer term (several decades) flow records. This study indicated that the Coastal Plain streams in North Carolina with long-term USGS flow records all experienced 7Q10 declines between 1998 and 2011. Although the causes of these declines were not isolated, they are likely associated with drought occurrence and possibly influenced by increased water use. More work is needed to evaluate the influence of water use on low flows in the North Carolina Coastal Plain. Currently, USGS is conducting a low flow study of North Carolina sites with long-term discharge records, including the Trent River station near Trenton and results are expected by 2025.

Discharge along the Trent River is typically lowest during the summer months (May-August), however during years with limited tropical storm activity, low flows may also occur in the fall (Figure 4). Public water supply records (https://www.ncwater.org/WUDC/app/LWSP/) suggest that summer is also the period with greatest water use in the watershed (Appendix B). Over time, the extreme low flows along the Trent at the USGS gage near Trenton have been declining. For example, the lowest daily flow from the decade from 1950-1960 was 1.3 cfs, whereas in the most recent decade (2010-2020) the lowest daily flow was 0.46 cfs (Figure 5). Over the period of record (1951-present) the USGS station never recorded 0 flow (no flow), but a minimum daily flow of

0.18 cfs was recorded during the drought of 2008 (August 27, 2008). The general pattern of declining extreme low flows over time in Figure 5 suggests there is a chance that no flow at the USGS gage near Trenton may occur in the future during extreme drought.

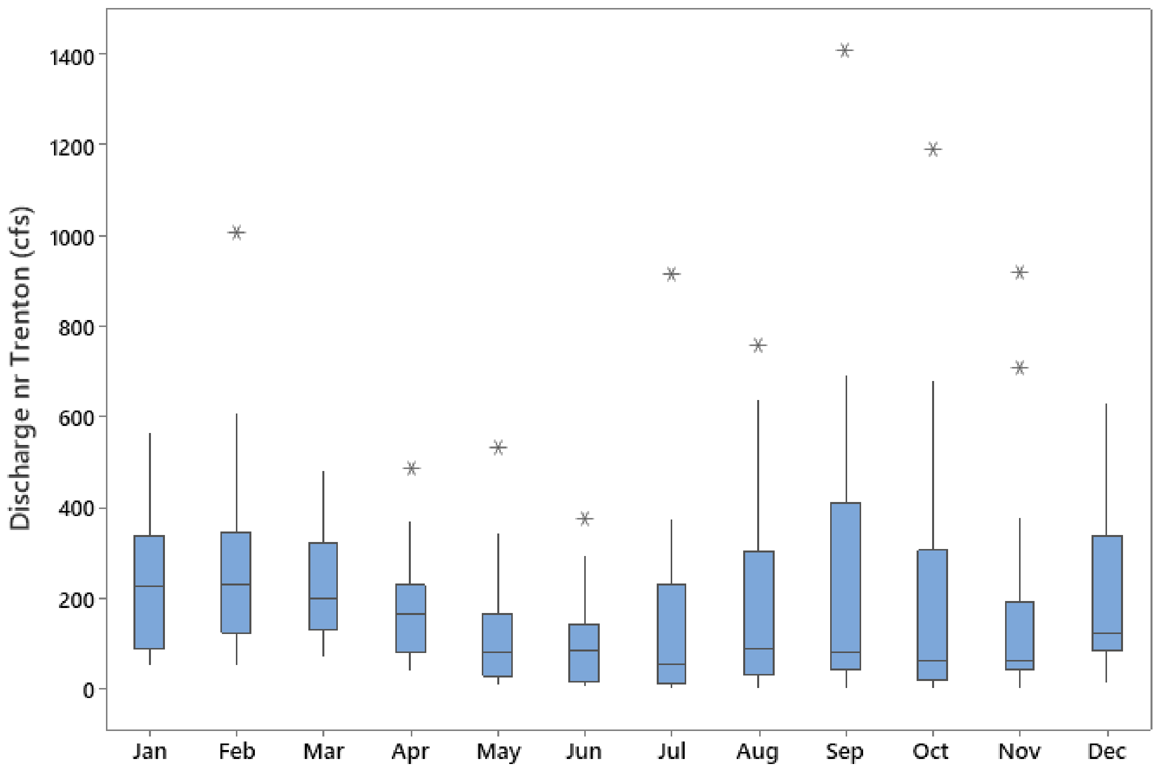


Figure 4. Boxplots of mean monthly discharge at the Trent River near Trenton USGS gage for the period of 2000-2020. Note: one high flow data point (6,421 cfs) associated with Hurricane Florence in September 2018 was excluded to enhance visibility of the boxplot ranges.

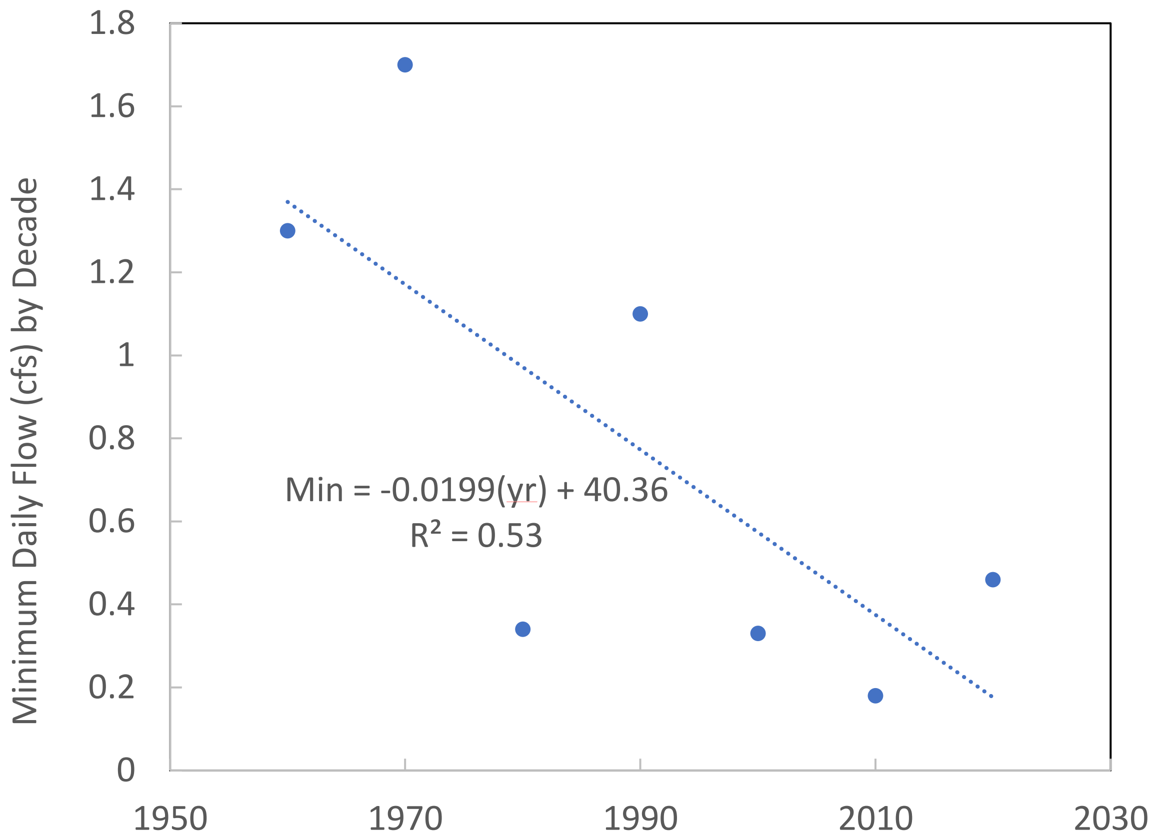


Figure 5. Minimum daily flow by decade at the Trent River near Trenton USGS gage.

As previously mentioned, the duration of low flows may also influence the aquatic habitat and water quality. The 10th percentile flow for the Trent River near Trenton is approximately 7.5 cfs. For the period of record, the number of days per year with flows below 7.5 cfs has ranged from 0 to 161 days. The longest duration occurred during drought conditions in 1954. In general, the number of days with low flow conditions per year showed increases since the 1970s associated with drought cycles, with a cluster of years with extended durations of low flow conditions between 2007-2011 associated with drought conditions (Figure 6). Over the past decade, generally wetter conditions have resulted in shorter periods of low flows on the Trent. However, during the study period (Summer 2021-Winter 2022), drought conditions existed in the watershed (Figure 6).

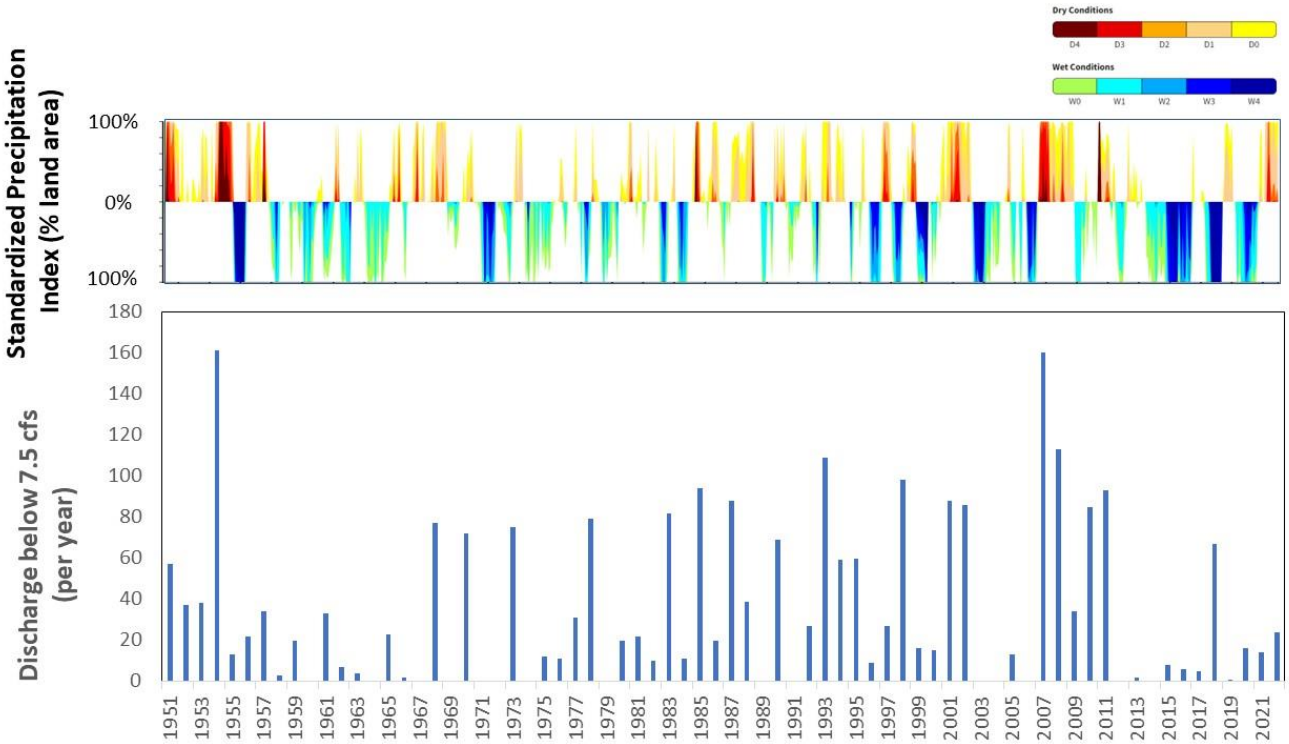


Figure 6. Days per year when discharge at the Trent River USGS gage near Trenton was below the 10th percentile (7.5 cfs) compared with the standardized precipitation index for Jones County from 1951-2022.

During 1996-2006, USGS developed a continuous discharge record at the Pollocksville gage (Figure 7). This record showed that bi-directional flows occur at this site, and due to tides and wind there are brief periods when surface water flows inland (as indicated by negative discharge). Typically, inland flows occur during periods when low flows are occurring at the upstream near Trenton gage. During tropical storms, inland flows associated with wind and storm surge can have a large magnitude, followed by a reversal associated with high flows from the storm precipitation.

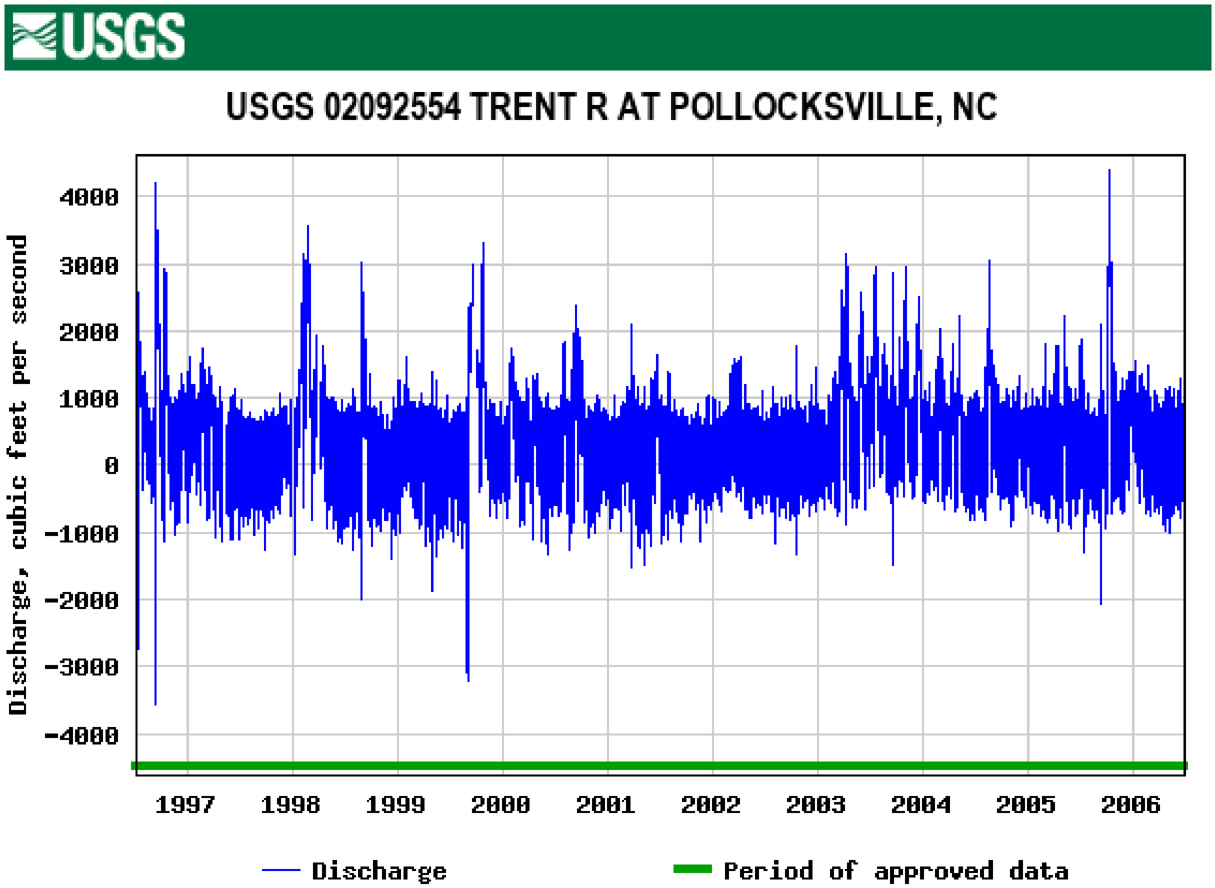


Figure 7. Discharge data collected by USGS at the Pollocksville gage (30-minute intervals) from 1996-2006. Negative discharge indicates surface water was flowing inland (towards Trenton).

Low flow conditions were shown to have a greater influence on water level in the upland portions of the Trent River watershed (Figure 8). A comparison of stream stage variability at the USGS gage near Trenton (upland) with the downstream (lowland) gage at Pollocksville revealed that low flows have a greater influence on stage in the upland areas (Figure 9). Based on the similarity in water level variability at our water level stations and the USGS gage at Pollocksville downstream of Trenton and the FIMAN water level gage at Trenton, the data suggest that the extent of tidal/downstream influence on water levels extends to approximately Trenton (station B in Figure 3) and in and around Trenton tidal influence may occur during low flows, but upstream of Trenton, as indicated by the USGS gage levels, there is currently no significant tidal influence. These data indicate that upstream controls on water level are dominant upstream of Trenton and between Trenton and Pollocksville the influence of estuarine water levels reduces the likelihood of extreme low stages. Earlier work by USGS (Giese et al. 1985) indicated that the upstream extent of tidal effects on the Trent River were thought to be about halfway between Pollocksville and Trenton, or about 35 miles upstream from its mouth at New Bern. Data currently being collected at Trenton through the FIMAN network suggests that tidal influence on water levels can periodically be observed at Trenton. Sea level rise influence on Trent River water levels during the past 35+ years may have resulted in a slight upstream shift in tidal influence since the earlier USGS study.

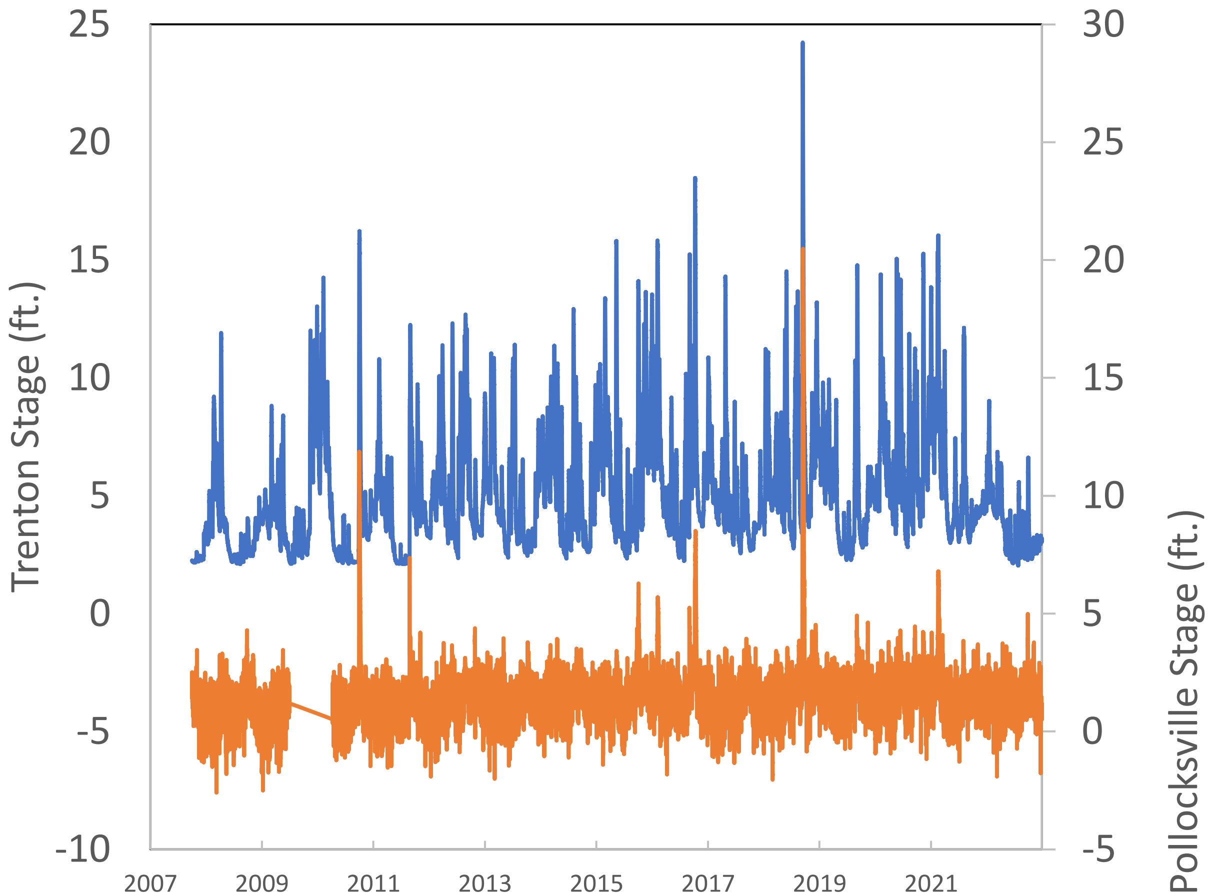


Figure 8. Stage data collected by USGS at the Pollocksville and Near Trenton gages (15-minute intervals) from 2007-2022.

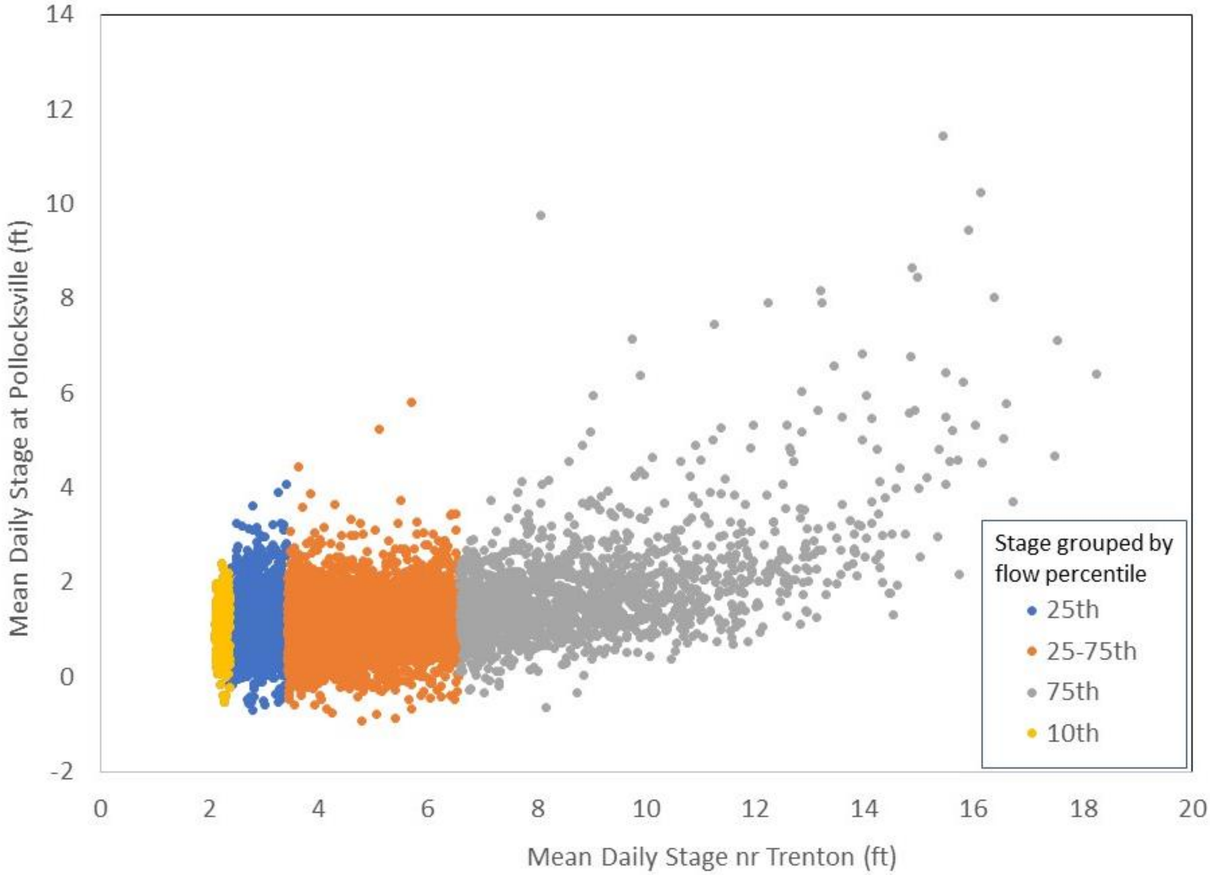


Figure 9. A comparison of daily stage variability (2000-2019) at Pollocksville and Near Trenton gages. Stage data is grouped by flow percentile. Low flows have less influence on stage at Pollocksville. High flows (>75th percentile~222 cfs) have greater influence on stage.

There is evidence that the stream stage at Pollocksville is influenced by sea level rise over time. A comparison of the mean annual stream stage at Pollocksville with the sea level measured at the NOAA tidal gage at Beaufort shows a similar trend of rising water levels over time, whereas the stream levels at the USGS gage near Trenton show substantial variability in water levels with no discernible trend (Figures 10 and 11). These data suggest that the influence of rising sea level should be considered for ecological flow considerations for coastal rivers, with likely implications for stage and habitat variability and saltwater intrusion, particularly in the riverine-estuarine transition zone.

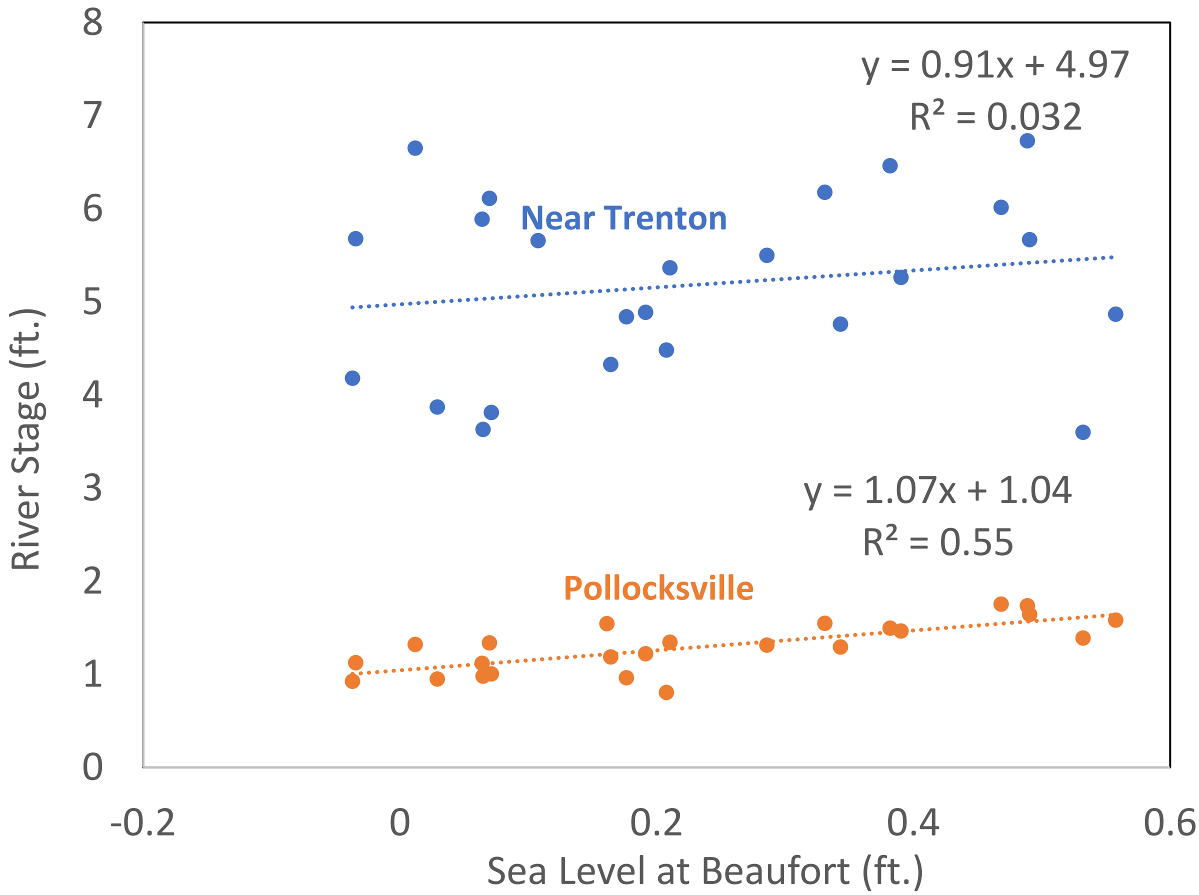


Figure 10. Mean annual river level at USGS near Trenton and Pollocksville gages compared to mean annual sea level at Beaufort NOAA tidal gage from 1998-2022.

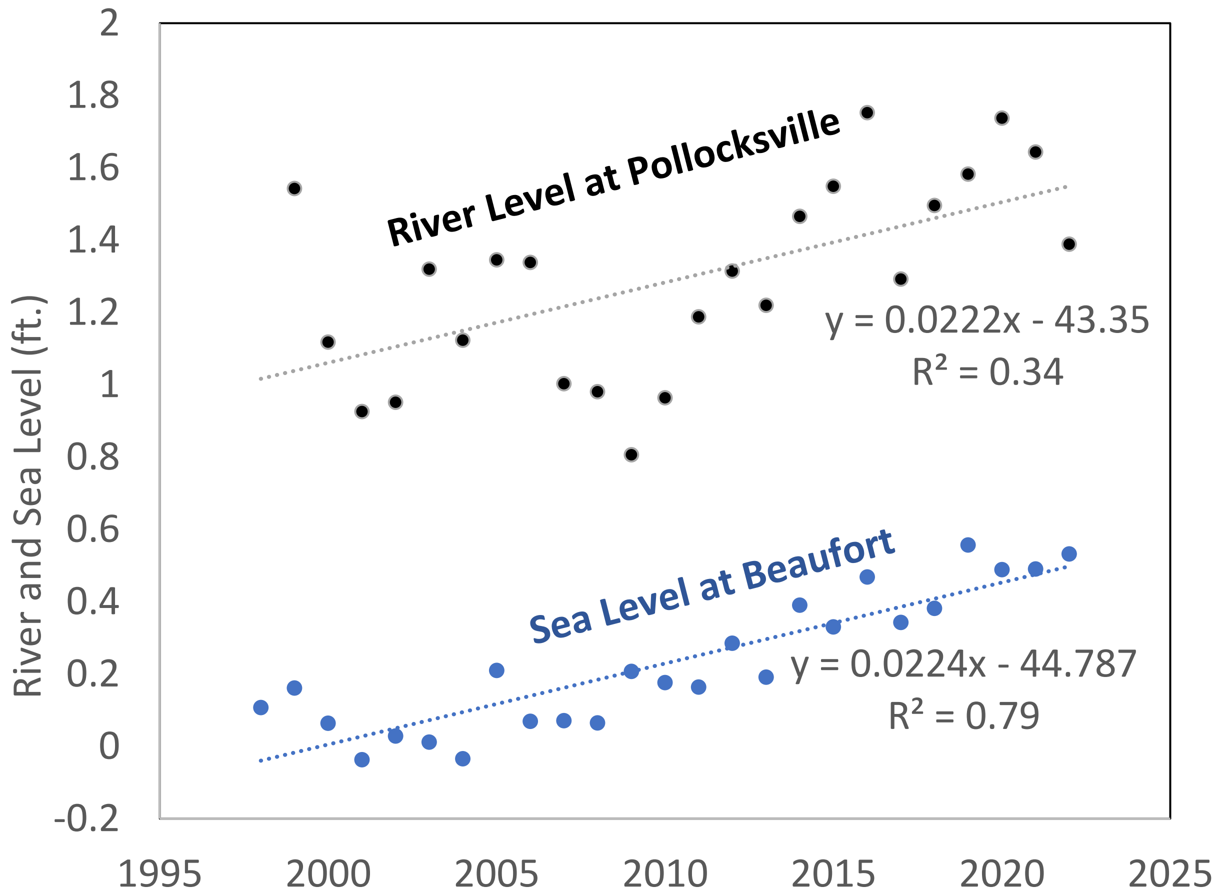


Figure 11. Mean annual river level at Pollocksville (USGS) and sea level at Beaufort (NOAA) from 1998-2022.

6.4 Flow-Water Quality Interactions

The freshwater inputs to coastal rivers and estuaries play a major role in the dynamic balance between freshwater and saltwater in the rivers and estuaries. The ecological communities are determined by the temporal and spatial patterns of freshwater and saltwater mixing. The dynamics and location of the freshwater-saltwater mixing zone is influenced by the freshwater flows (upstream controls) and the ocean estuarine water levels and salinities (downstream controls) (Figure 12). In the riverine-estuarine transition zone salinity is typically lower during moderate to high flow events and elevated salinity can occur during low flow events. During low flows, the freshwater-saltwater interface can migrate upstream. The extent and duration of saltwater incursions can affect flora and fauna. One consideration for coastal systems is that during low flow conditions, short duration (hours-months) inland saltwater intrusion events may occur and extend to inland reaches that are typically fresh. The effects of these events on coastal rivers in the Albemarle-Pamlico drainage basin has not yet been thoroughly evaluated but may impact freshwater aquatic communities.

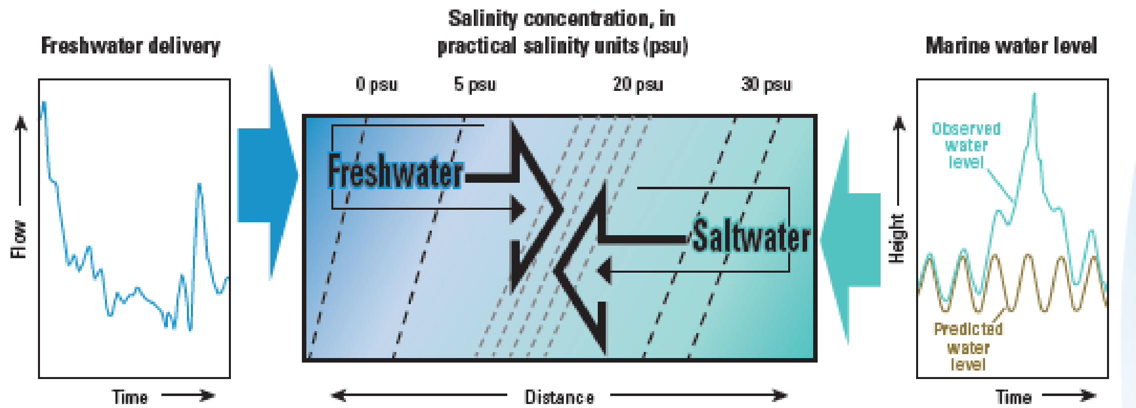


Figure 12. Estuarine salinity dynamics are influenced by freshwater inputs and estuarine water levels (wind and tides). Modified from Conrads et al. (2018).

Increased salinity during low flow events can influence fisheries (Conrads et al. 2018). For example, Doering and Wan (2017) found that low flows could reduce blue crab landings in the Caloosahatchee Estuary in Florida. Similarly, Kennedy and Barbier (2016) found that decreasing flows led to increased salinity and reductions in blue crab landings in Georgia, USA. In Apalachicola Bay in Florida, Havens et al. (2013) showed that a decrease in freshwater flows to the Bay resulted in a reduction in oyster production.

In ecological flow studies of coastal rivers and estuarine systems, there is often limited ecological and water quality data for assessment (Chilton et al. 2021). Since salinity plays a major role in the aquatic ecology of these systems, it has been suggested that salinity data can be used as a proxy for the relationship between freshwater inputs and the functionality of the estuarine system (Peñas et al., 2013, Chilton et al. 2021).

The NC DEQ water quality monitoring data locations, from upstream to downstream (near Trenton, Pollocksville, Trent Woods, and New Bern (Fig. 3) allowed for the evaluation of spatial and temporal variations in SC along the Trent River. As sampling moved further eastward down the Trent River across the four long-term NCDEQ monitoring stations, there was an overall increase in SC downstream with the transition from riverine to estuarine conditions. These long-term SC data were used to evaluate the influence of watershed location and freshwater flows on salinity in the Trent River system (specific conductivity was used as a surrogate for salinity). Near Trenton the specific conductivity maximum was 303 uS/cm during the period of 1997-2020 and indicated freshwater conditions. At Pollocksvillle (~12 mi/20 km inland), freshwater conditions dominated, except for during low flow events when SC was elevated > 500 uS/cm, indicating brief periods of saltwater intrusion that extended for several months during drought conditions, The maximum SC (5095 uS/cm) was measured during drought in October 2007. The Trent Woods site (~ 3 mi/5km inland) commonly had elevated SC during periods when SC was elevated downstream at the Neuse River estuary. Typically, elevated SC at the Trent Woods site corresponded with low flow conditions and these elevated salinity periods extended for several months. During the drought of 2007-2008, the maximum SC at Trent Woods was 20,276 uS/cm in August 2008. Typically, when SC was elevated in the Neuse River estuary, SC was elevated at Trent Woods. During the periods when downstream SC was elevated and low flow conditions persisted, the likelihood for elevated SC (saltwater incursions) increased at Pollocksville (Fig. 13).

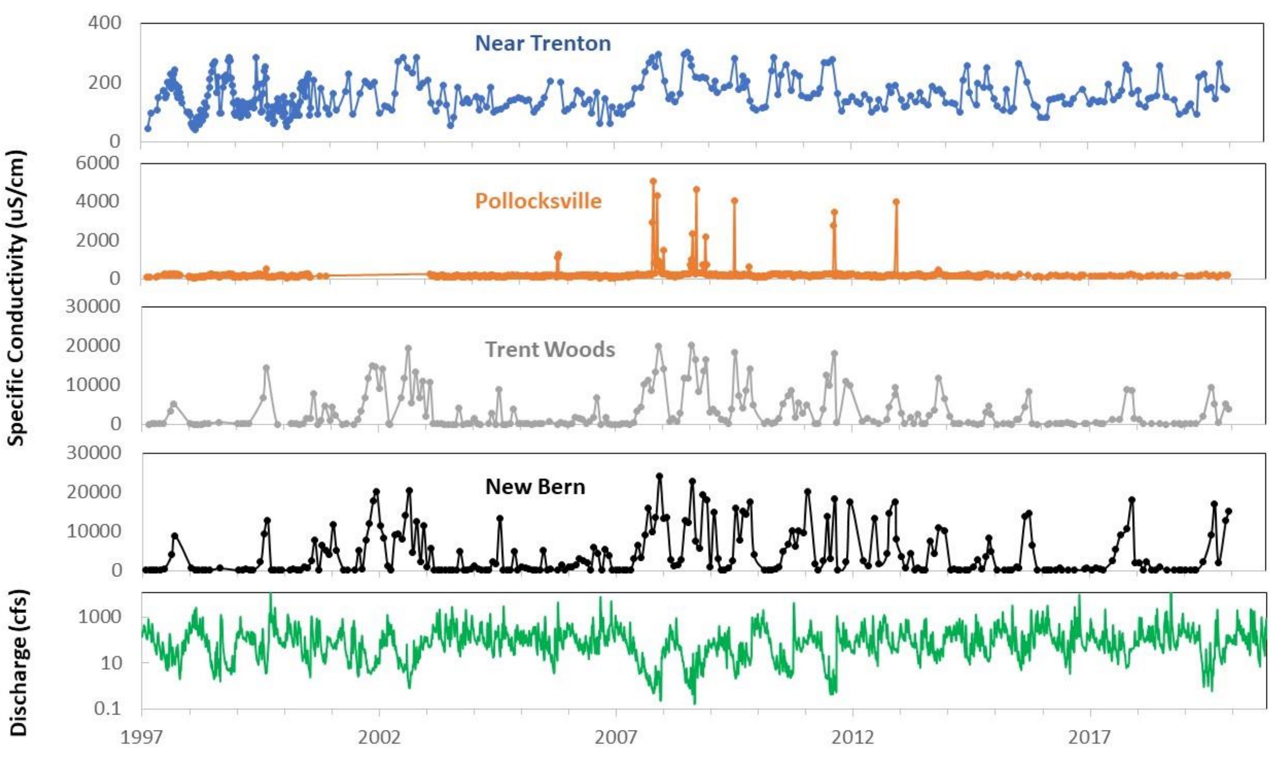


Figure 13. Specific conductivity data from NC DEQ ambient monitoring stations at sites along the Trent River from upstream near Trenton, Pollocksville, Trent Woods, and New Bern (estuary). Discharge data is from the USGS gage near Trenton. Note the change in scale for specific conductivity as estuarine influence increases downstream from near Trenton to New Bern.

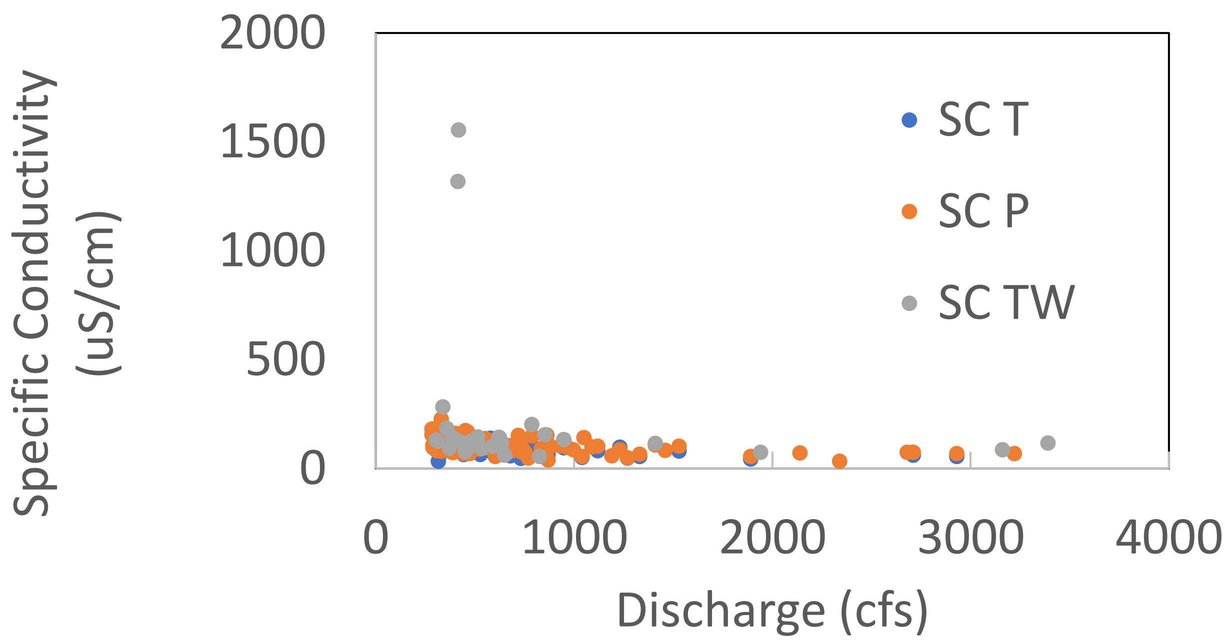


Figure 14. During higher flow conditions (> 300 cfs) water quality was similar from near Trenton to Trent Woods and SC was typically below 300 uS/cm, indicating freshwater conditions during high flows.

When discharge near Trenton was elevated greater than 300 cfs, the SC was typically below 300 uS/cm, indicating freshwater conditions were dominant along the Trent River (Figure 14). Flow vs. SC data was compared directly for the DEQ ambient monitoring sites. These data showed a general inverse pattern between river discharge at the USGS near Trenton gage and specific conductivity at the NC DEQ ambient monitoring stations (Figure 15). At the upstream site near Trenton freshwater conditions existed year-round, with dilution resulting in lower conductivities during high flows. At Pollocksville, there was evidence of saltwater intrusion on several dates. At the downstream sites at Trent Woods and New Bern, the elevated specific conductivity was common at low flows, with freshwater conditions occurring periodically when discharge was elevated.

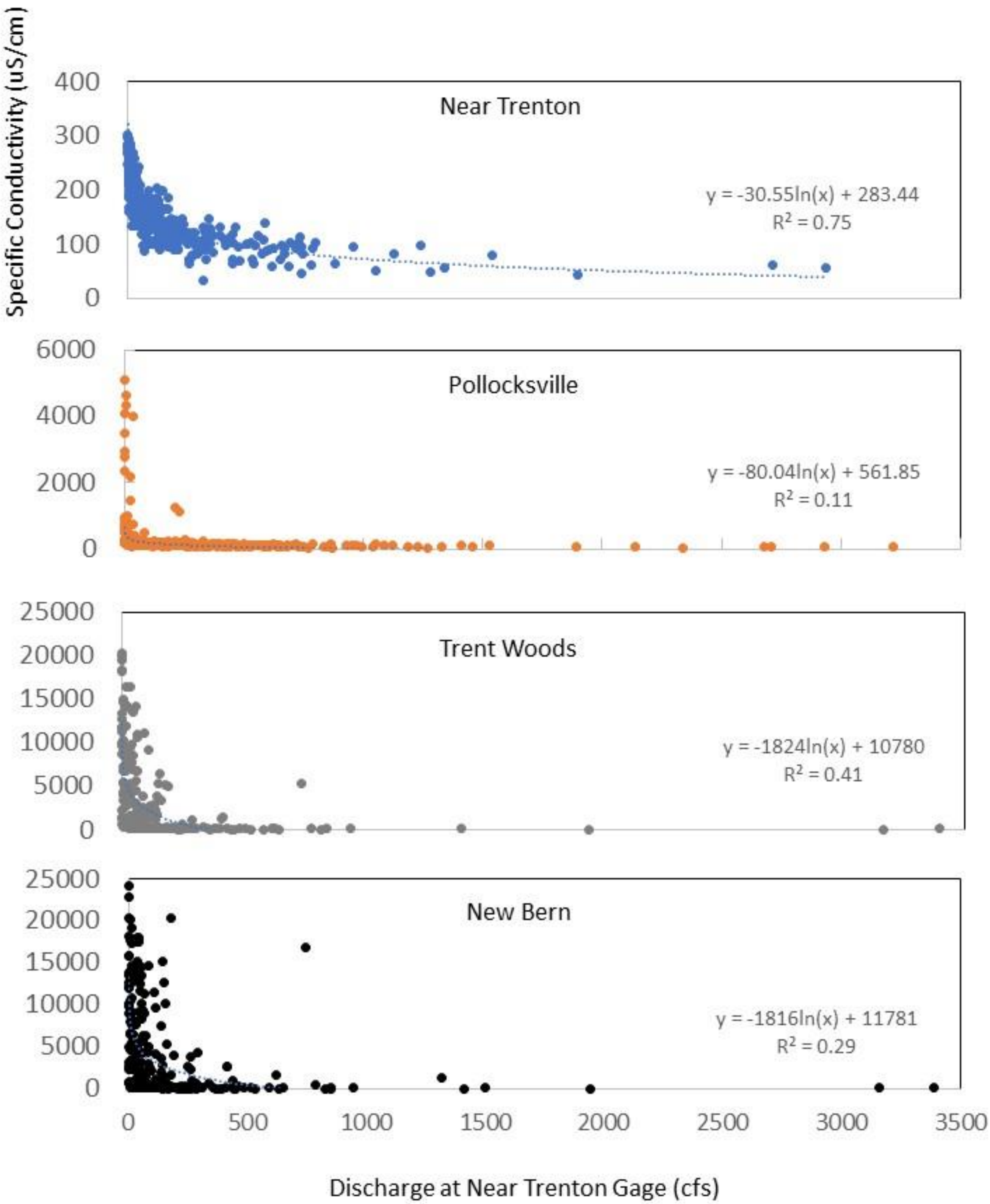


Figure 15. NC DEQ specific conductivity data vs daily average discharge at USGS near Trenton gage (1996-2020).

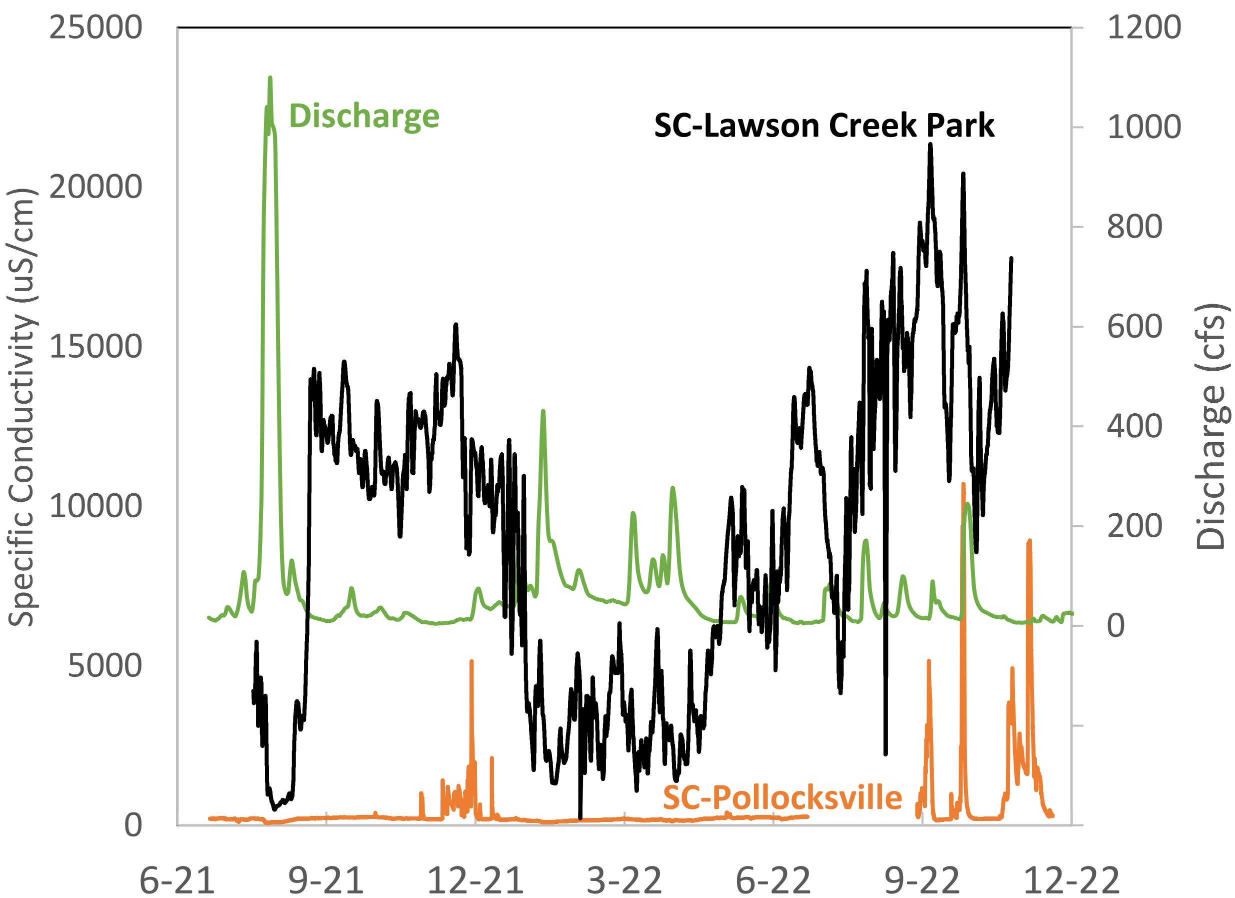


Figure 16. Specific conductivity logger data at Lawson Creek Park (estuarine) and Pollocksville (riverine) indicated saltwater intrusion events at Pollocksville that corresponded with low flow conditions at the USGS gage near Trenton. Loggers were deployed from July 2021-November 2022. The data gap at Pollocksville in the summer of 2022 was due to logger malfunction.

Specific conductivity loggers installed for this study and longer-term NC DEQ ambient monitoring revealed that the Trent River was typically salty at River Bend and downstream at Lawson Creek Park during the period of July 2021 to November 2022, with the exception of periods with high discharge (Figure 16). At Pollocksville, there were several brief periods when specific conductivity was elevated greater than 500 uS/cm, with the longest duration of 25 days in October-November 2022 (Figures 15 and 16). These saltwater incursion events typically occurred during low flow periods. An example of a series of saltwater incursion events during November-December 2021 and October-November 2022 is provided in Figure 17. A comparison of stream stage at Pollocksville and conductivity spikes suggested that wind and tidal effects on water levels can influence inland migration of saltwater during low flows (Figure 18). When low flow conditions occur, if the downstream waters have elevated salinity the likelihood of inland saltwater intrusion increases. These data suggest that salinity conditions in the Neuse estuary also play a role. In addition, water treatment residuals from the Jones County Water Treatment Plant are discharged to the Trent River near Pollocksville, which may also influence salinity along this reach.

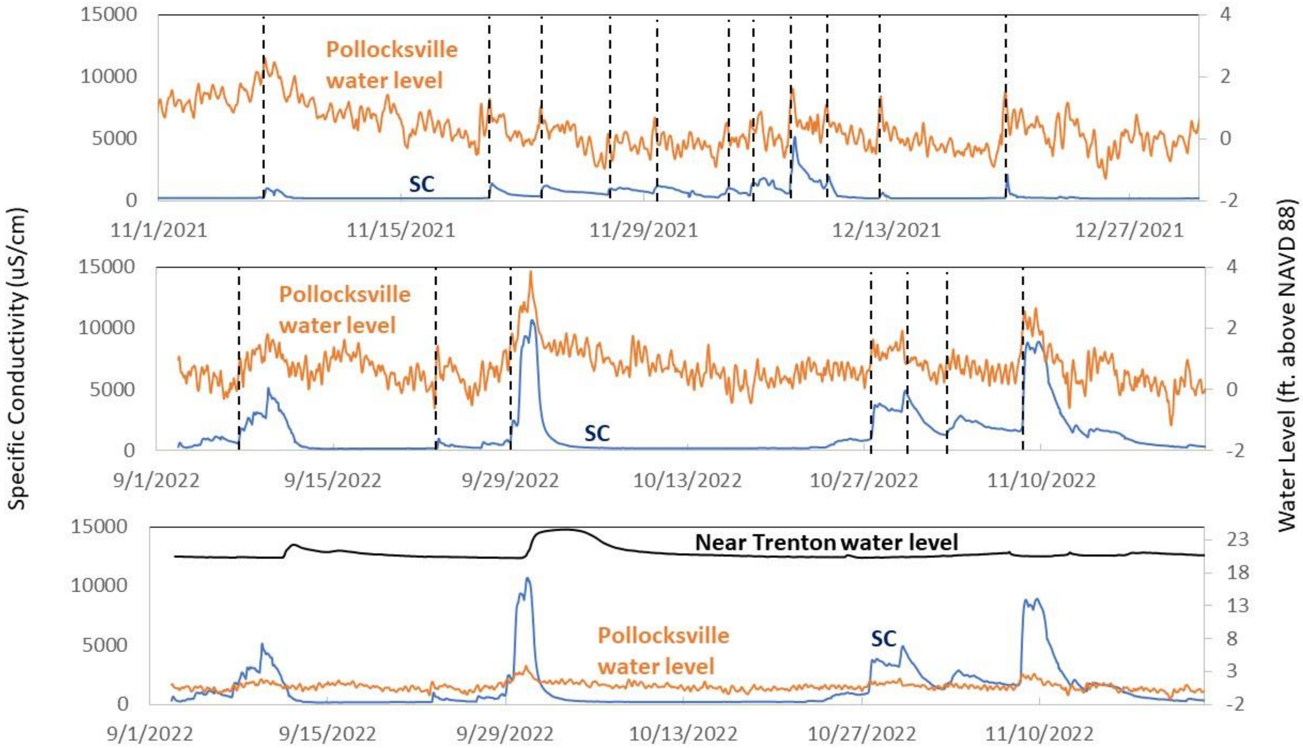


Figure 17. Two periods of saltwater incursions at Pollocksville were observed based on the specific conductivity (SC) loggers, during November-December 2021 and September-November 2022. Spikes in SC indicative of saltwater incursions typically corresponded with spikes in water level at Pollocksville. During these periods water levels at the USGS near Trenton was relatively stable for the 2021 period, during the 2022 period there were two runoff events that led to dilution. Overall the data indicated that water level increases near Pollocksville that were not related to discharge events were likely the result of wind events that could transport salinity further inland to Pollocksville.

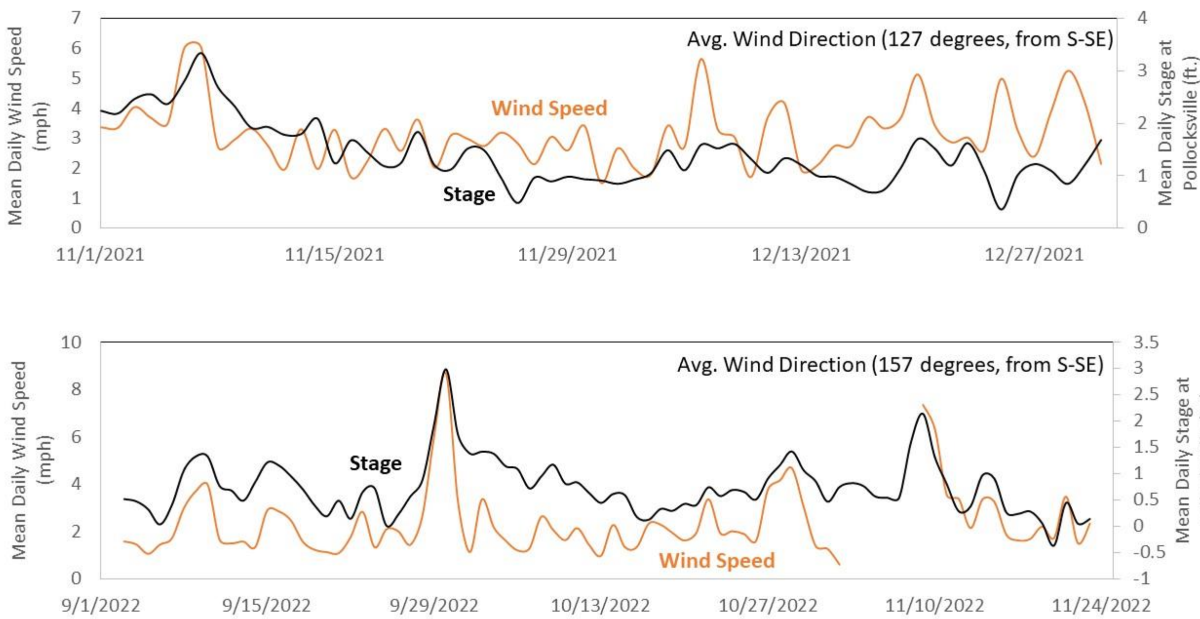


Figure 18. Wind speed data from the FIMAN gage at Trenton compared to stage data at Pollocksville suggested that wind-related increases in stage can lead to inland migration of salinity at Pollocksville.

The longer-term specific conductivity data at Pollocksville indicate that recent drought and meteorological conditions have a greater influence on saltwater intrusion at this site than the longer-term influence of sea level rise. Earlier work by USGS (Giese et al. 1985) included specific conductivity monitoring along the Trent River between 1959-1961. Their work documented the maximum upstream extent of saltwater intrusion along the Trent about 4.5miles upstream from Pollocksville caused by winds from Hurricane Hazel (1954). They documented the influence of wind conditions on the salinity in the riverine-estuarine transition zone. Their research indicated that maximum estuarine water levels near New Bern coincided with winds from 60 degrees east. When water levels are elevated in the lower portions of the Trent due to wind and tides, and water levels upstream are low due to low flows, and high salinity conditions exist in the Neuse Estuary, saltwater has a greater likelihood of migrating inland.

Overall, the data suggested that water quality along the tidal reaches of the Trent River is highly influenced by flow conditions. An additional SC data set from USGS collected in the 1960s was compared to the recent NC DEQ data (2014-2019) to evaluate if SC has increased over time. This comparison suggests that median SC has increased at the site over time, presumably related to salinization (Figure 19).

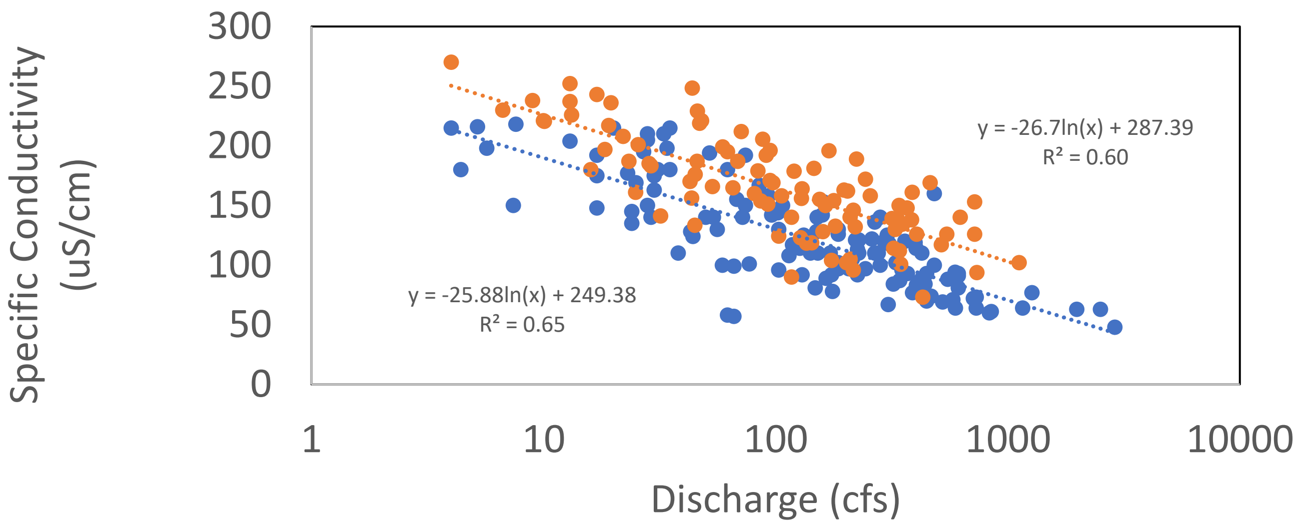


Figure 19. Discharge vs SC at Pollocksville comparison between the 1961-1966 USGS data (blue dots) and the 2014-2019 NC DEQ data (orange dots). Median SC for the 1961-1966 period was 116 uS/cm and for the 2014-2019 period was 160 uS/cm.

Spatial variations in specific conductivity and salinity in the riverine-estuarine transition zone were further studied through longitudinal surveys during periods with various flow conditions on November 13, 2021 (discharge: 5.5 cfs); March 8, 2022 (discharge: 46 cfs); and June 24, 2022 (discharge: 8.4 cfs). These surveys revealed that the upstream extent of salinity at 2 ppt (a threshold of sensitivity indicated for some wetland trees and fish) extended furthest inland during the June survey (Figure 20). There was limited wetland condition information along the Trent River, but the National Wetland inventory has mapped the majority of wetlands fringing the river as freshwater systems.

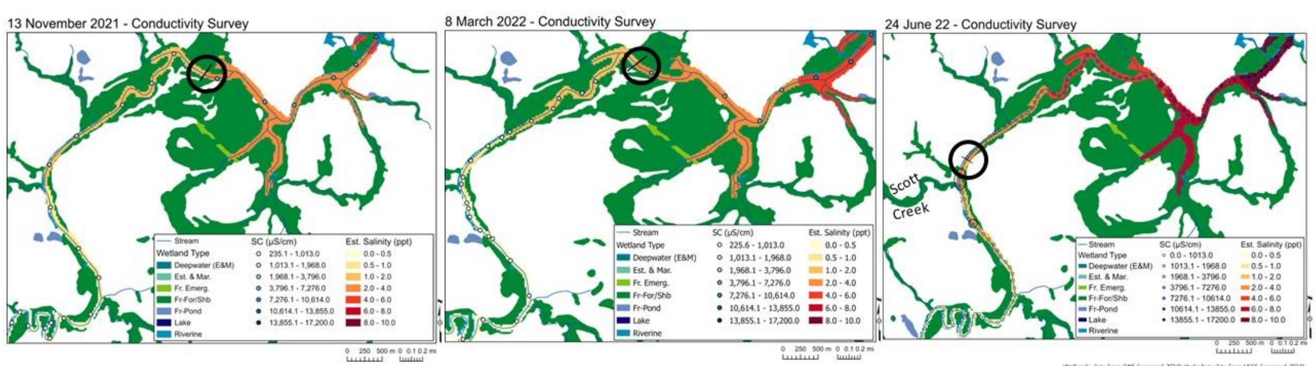


Figure 20. Longitudinal SC surveys from Pollocksville to River Bend conducted on Nov. 21, 2021, March 8, 2022, and June 24, 2022. Black circle indicates upstream extent of 2 ppt salinity.

6.5 Seasonality of Salinity Patterns

The seasonal variability of specific conductivity along the Trent River was analyzed from NCDEQ data. For all sites there was a general seasonal pattern of lower SC values measured in the winter and spring months and larger values measured in summer and fall. However, for the estuarine sites (Trent Woods and New Bern), elevated SC values could also occur in the earlier winter months (Dec.-Jan.) (Figure 21) suggesting a slight time lag associated with freshwater inputs from the watershed. The near Trenton site exhibited freshwater conditions year-round, whereas at Pollocksville, SC outliers > 500 uS/cm between July and January indicated temporary incursions of saltwater could influence the monthly grab samples at this site within the riverine-estuarine transition zone. At Pollocksville the highest median monthly SC values occurred in the late fall-early winter. In the estuarine segments of the watershed (Trent Woods and New Bern) there was a wider range of monthly specific conductivity values in contrast to the upstream sites. April shows the smallest range in monthly specific conductivity values for the estuarine sites, coinciding with higher freshwater flows (Figure 21).

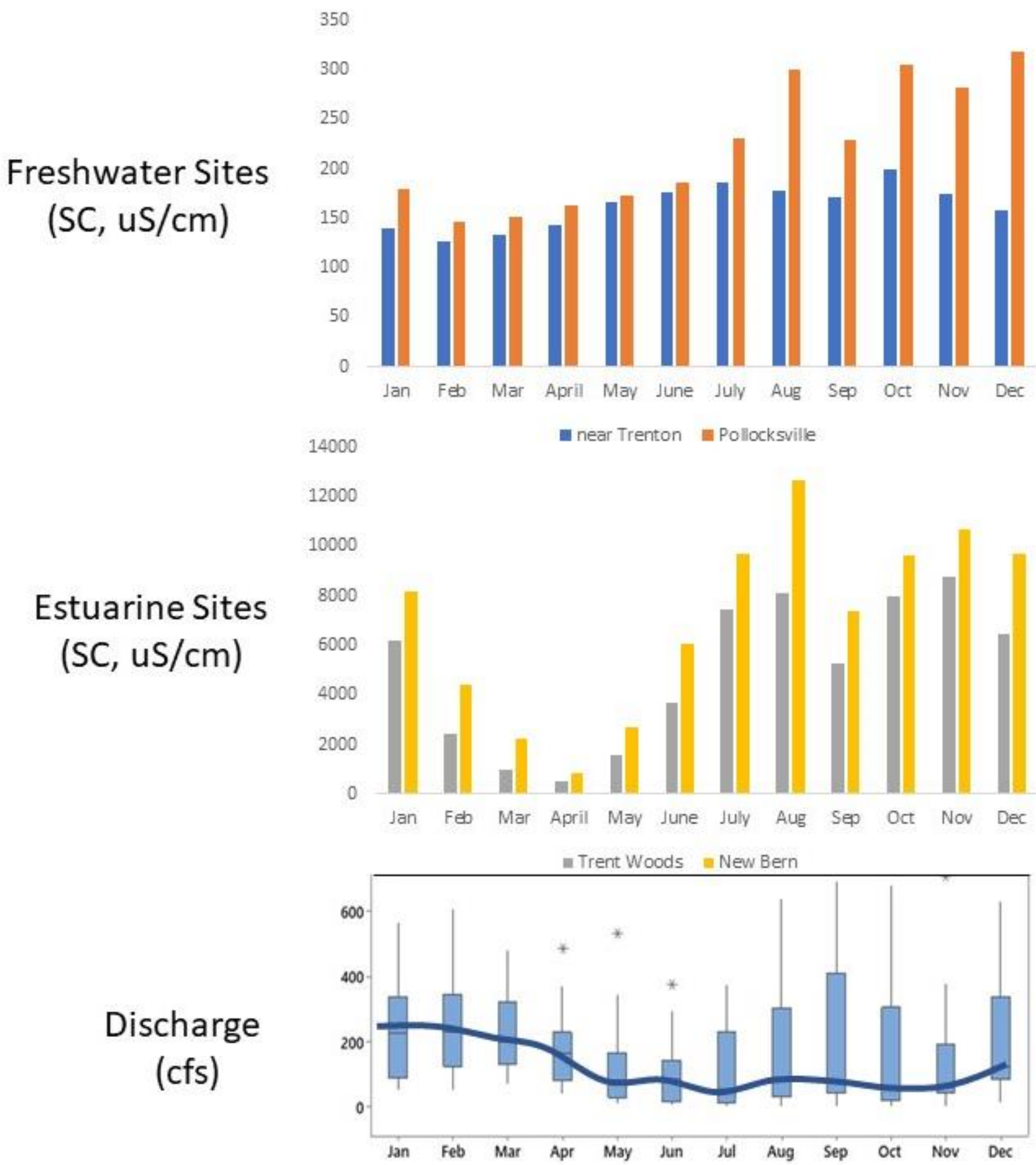


Figure 21. Mean monthly SC data at the NC DEQ ambient monitoring stations (2000-2019) indicated lower SC in the winter and spring corresponded with higher discharge conditions at the USGS gage near Trenton and a greater seasonal range of SC with proximity to the estuary. Note the difference in scale for SC between the freshwater sites (upper graph) and estuarine sites (middle graph).

6.6 Ecological Considerations

6.6.1 Salinity and Biological Indicators of Salinity Regime

Water availability is a primary environmental control factor of living things. It affects structure and function at many levels from the subcellular to organismal. Effects extend beyond the individual organism to changes in community structure and ecosystem function. The proximal controls over water availability for ecological flows are salt concentrations and actual quantity of water within the habitat (i.e., wetting and drying). Salt concentrations are measured as salinity or estimated through conductivity (or specific conductance).

Research on ecological flows are generally focused on the community level. Ecosystem function is recognized as linked to community structure, and a broader view of ecological flows includes this recognition. The primary communities we considered as indicators of ecological flows are riparian wetland vegetation and fishes. Other fauna and flora may also be appropriate but were beyond our scope. Benthic invertebrates have been used to indicate the salinity regime in both Coastal Plain rivers and estuaries (Eaton 1994, Montagna 2021). Many benthos have the advantage of being sessile or nearly so. Thus, they integrate the salinity regime across time in ways better than mobile nekton or drifting plankton. Also, they are likely to respond to salinity change in shorter time spans than wetland vegetation. Thus, future efforts may wish to include this community.

6.6.2 Wetland Vegetation as an Indicator

We addressed the effects of salt on wetland vegetation through wetland tree sensitivity. Riparian forests border many of the rivers within the Coastal Plain of North Carolina. These forests dominate natural areas where waters are fresh and are replaced by marshes as salt concentrations begin to rise within lower reaches of rivers and estuaries. Trees, shrubs, and then grasses and rushes are foundational species, respectively. As such, they serve as important indicators of ecosystem function. The two primary natural factors that contribute to the replacement of riparian forest by marshes are salt and flooding, often in combination (Connor et al. 1997, Herbert et al. 2015). Therefore, we examined the literature for the sensitivity of wetland trees to salinity and considered flooding as contextual.

The literature on wetland tree sensitivity to salinity spans a diversity of locations, tree species, study designs and response variables. A summary of selected references is shown in Table 11. Most studies we reviewed were for locations within the Southeast and Gulf Coast states. We made no distinctions in interpretation of results based on state. Some studies considered overall community response, but most focused on one or a few species. The most studied species was baldcypress, but other wetland tree species received consideration. Study design included observations across space and time involving different salinity and flooding conditions and experimental studies. Experiments included both laboratory/greenhouse and in situ experiments that altered salinity. In some cases, both salinity and flooding regime were altered. As would be expected, the duration of studies varied considerably. We used all appropriate study designs and other reviews in our synthesis. Finally, a variety of response variables were used throughout the studies. Growth rate, as measured in a variety of ways, and mortality were the two most common response variables. Further, these response variables were considered for various life stages from seeds and seedlings to mature trees. Our goal was to use as much of this information to identify salinity thresholds that may be detrimental in some way to wetland tree species populations or communities in general. Thus, we only used studies that provided clear values or ranges of salt concentrations that detrimentally affected plants.

Table 11. Summary of selected references on salinity effects on wetland trees.

Authors	Year	Study design	**State**	Species or taxa	Response metric	Response	Threshold salinity
Allen et al.	1996	Review	LA	*Taxodium distichum*	Seedling growth & others	Less growth with both flooding and salt	Varied some indication 2-4 ppt
Anderson	2020	Greenhouse experiment, 2 pulses (0 to 6 ppt salinity, esp 0 and 3) on seedlings (mostly 1 y)	NC	6 species(*Acer rubrum, Juniperus virginiana, Pinus taeda, and Taxodium distichum*)		A. *rubrum* and *Q. nigra* above & belowground biomass decrease 4-6 ppt growth rates of seedling heights were consistently reduced in *A. rubrum, J. virginiana, P. taeda* and *T. distichum* (77%, 81%, 79%, and 96% respectively) when exposed to salinity > 4 ppt See Figure 2.14 for other results	Numerous variables of growth and physiology. 3ppt had some effects. Of the six species studies included in this study, *A. rubrum* was the most sensitive, and *J. virginiana* was the most tolerant of increase salt exposure < 6 ppt.
Chambers et al.	2005		LA	Baldcypress, Water Tupelo	baldcypress - chronic >4ppt increases mortality & makes regeneration unlikely	Tupelo chronic >2 increases mortality	
Conner et al.	1997		SC	Baldcypress, Water Tupelo, Chinese Tallow, Green Ash	seedlings survival and growth (ht, root and stem growth)	No seedling mortality up to 10 ppt	Most reductions occurred between 2 and 10 ppt, especially with flooding.
Conner et al.	1998	Experiment, 1 yr seedlings chronic & pulse flood and salinity, 1 yr study	MS	Swamp chestnut Oak, Water Oak, Overcup Oak, Nuttal Oak	seedlings survival and growth (ht, root and stem growth)	flooding alone had effects but not as much as with salt; Overcup most tolerant to salt	all species mortality and/or damage flooded or watered at 2 and 6 ppt
Krauss et al.	2009		SC GA LA	Baldcypress	Saplings from tidal and non-tidal areas in common garden with and without tides freshwater and `2ppt	Little sign of selection for tide vs non-tide preference, numerous salinity effects at 2 ppt under flooded conditions.	Effects at 2 ppt
Krauss and Duberstein	2010	Field comparison of transitional saline and fresh sites	SC	Baldcypress	sapflow	Less flow in saline site; size of trees mattered.	Not determined

Krauss et al.	2000	Field planting of seedlings in 3 sites of different salinity regimes	LA	Baldcypress	seedling growth & survival	Site with highest salinity (mean = 2 ppt) had lowest growth	mean 2 ppt first season but higher in August up to 15 ppt
Light et al.	2002		FL	*Quercus virginiana, Magnolia Virginiana,* etc.			5 ppt was average salinity in water and ~4 ppt in soils at/near tree line (last forest before marsh) in Suwannee
McLeod et al.	1999	One year seedlings in pots, treated with chronic flooding & pulse, fresh and salt (2 and 6 with pulse of 30	MS.	*Quercia Lyrata, Q. michauxii, Q. nigra, Q. nuttalli*	Photosynthesis, conductance, timed water potential	All showed effects to 2 and 6 with length of time to response species specific. Greatest effects during chronic flooding	2 in most cases but more severe with 6
Taillie et al.	2019	Field measures in multiple sites over 13 yrs. Vegetation change vs elevation and salinity.	NC	Trees, saplings. shrubs. Grass, snag	Abundance.	Negative response of all plant categories re: salinity not elevation	Used linear relations so none identified.

Our interpretation of the literature on wetland tree response to salinity is summarized in Figure 22. We identified two consensus thresholds: a minimal salinity for which some negative response was noted and a higher threshold salinity that demonstrated mortality or at least significant detriment. These thresholds were estimated at 2 and 6 ppt (3.8 and 10.7 mS/cm), respectively. Each bar represents the interpretation from at least one study. For example, information for red maple came from Anderson (2020), whereas we used several studies of baldcypress (Allen et al. 1996, Chambers et al. 2005, Conner et al. 1997, Krauss et al. 2000, 2009, Powell et al. 2016). Seedlings of most species had initial thresholds around 2 ppt, and all showed severe effects by 6 ppt.

Studies of mature trees of individual species that provided thresholds were more difficult to find. Seedling studies were often greenhouse experiments, which are difficult or impossible for mature trees. We relied heavily on the review of Herbert et al. (2015) for the most general information. They provided global threshold estimates of impact on both seedlings and mature trees, shown in Figure 21. This undoubtedly includes many species not found in North Carolina and may be responsible for the higher upper threshold of 10 ppt. Powell et al. (2016) found 8-yr old baldcypress growth to be negatively correlated to soil chloride concentrations to salinities <5 ppt. However, studies of mature trees in the Southeast and Gulf states are compatible with an upper threshold of 8 to 10 ppt for baldcypress (Chambers et al. 2005, Light et al. 2002). The effects of increased harm to trees were shown in their replacement by marsh in the study by Light et al. (2002), shown as "Wetland forest presence" in Figure 22.

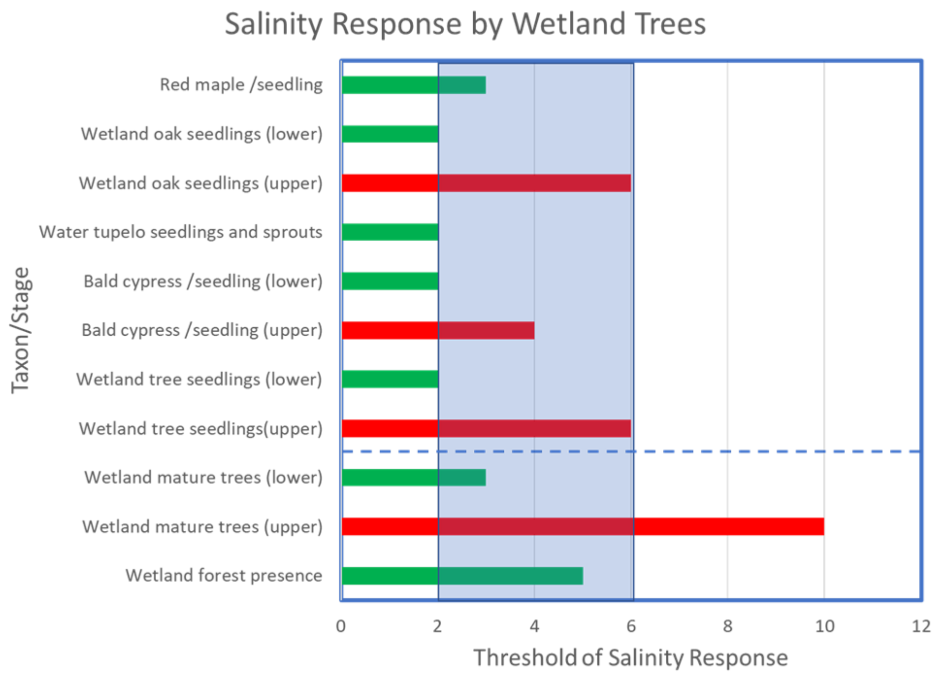


Figure 22. Salinity responses of wetland trees for the identification of threshold salinities for detrimental effects. (Selected data from literature is shown in Table 11.) Lower threshold of 2 ppt estimates consensus onset of detrimental effects. Upper threshold of 6 ppt estimates consensus salinity of demonstrated mortality or at least significant impact.

Wetland trees are not the only vegetative growth form that could be used as an ecological indicator of salinity response. Anderson et al. (2022) recently assessed the response of understory plants to soil salinity for the Albemarle-Pamlico Peninsula. Over 100 plant species were identified, and subsets were used in different analyses. Data included seedlings and saplings of trees and shrubs among other growth forms. They estimated two thresholds of soil salinity that altered community structure significantly. Their measures of salinity included Na^+ and Mg^+ plus Ca^+ as µg/g or µeq/g soil, respectively. Direct conversion to salinity (g/kg water) is not possible given the information provided, but the lower threshold is likely less than the 2 ppt we propose. This issue highlights the need to develop standards for conversions of units, sampling protocols and understanding of the relationships of salinity in surface water relative to soil salinity and its components.

Our analysis has provided a guide to establishing salinity thresholds on wetland trees but does not give the granular understanding of potential impacts by species that affect community structure. While species-specific thresholds may be unavailable, there is information on which species are tolerant to brackish water. Fortunately, Kristie Gianopulos with NC DEQ has considerable experience with riverine wetland plants in North Carolina and has helped us by providing information for Table 12. It includes plant species likely to be found along the Trent River and other eastern North Carolina rivers. We used this list during a field trip to the Trent River on June 24, 2022.

Table 12. Common wetland trees and shrubs in eastern North Carolina and their tolerance class to brackish and wetland conditions. Bold species names were found during our observations on June 24, 2022. Wetland indicator status is relative to where a species may be found: OBL for obligate wetland, FACW for facultative wetland, FAC for facultative, FACU for facultative upland.

Scientific name	Common Name	Tree/shrub =1 Other =2	Brackish Tolerant 1=yes	Fresh=1 Brackish= 2	Wetland Indicator Status
Acer rubrum	Red maple	1	0	1	FAC
Betula nigra	River Birch	1	0	1	FACW
Carpinus caroliniana	Ironwood	1	0	1	FAC
Fraxinus pennsylvanica	Green ash	1	0	1	FACW
Fraxinus caroliniana **Carolina Ash**	Carolina ash	1	0	1	OBL
Liquidambar styraciflua	Sweetgum	1	0	1	FAC
Nyssa aquatica	Water tupelo	1	0	1	OBL
Nyssa biflora	Swamp tupelo	1	0	1	OBL
Nyssa sylactica	Black gum	1	0	1	FAC
Quercus lyrata	Overcup oak	1	0	1	OBL
Quercus michauxii	Swamp chestnut oak	1	0	1	FACW
Quercus nigra	Water oak	1	0	1	FAC
Quercus phellos	Willow oak	1	0	1	FACW
Taxodium distichum	Baldcypress	1	1	1	OBL
Ulmus americana	American elm	1	0	1	FAC
Baccharis halimifolia	Eastern baccharis	1	1	2	FAC

Borrichia frutescens	Sea ox-eye daisy	1	1	2	OBL
Chamaecyparis thyoides	Atlantic White Cedar	1	1	2	OBL
Iva frutescens	Bigleaf marsh-elder	1	1	2	FACW
Morella cerifera	Wax myrtle	1	1	2	FAC
Hibiscus moscheutos	Rose mallow	2	1	2	OBL
Phragmites australis	Common reed	2	1	2	FACW
Spartina cynosuroides	Big cordgrass	2	1	2	OBL
Juniperus virginiana	Eastern red cedar	2	1	2	FACU
Juncus roemerianus	Black needlerush	2	1	2	OBL
Zizania aquatica	Northern wild-rice	2	1	2	OBL
Typha angustifolia	Narrowleaf cattail	2	1	2	OBL
Kosteletzkya virginica	Seashore mallow	2	1	2	OBL
Cladium jamaicense	Swamp sawgrass	2	1	2	OBL

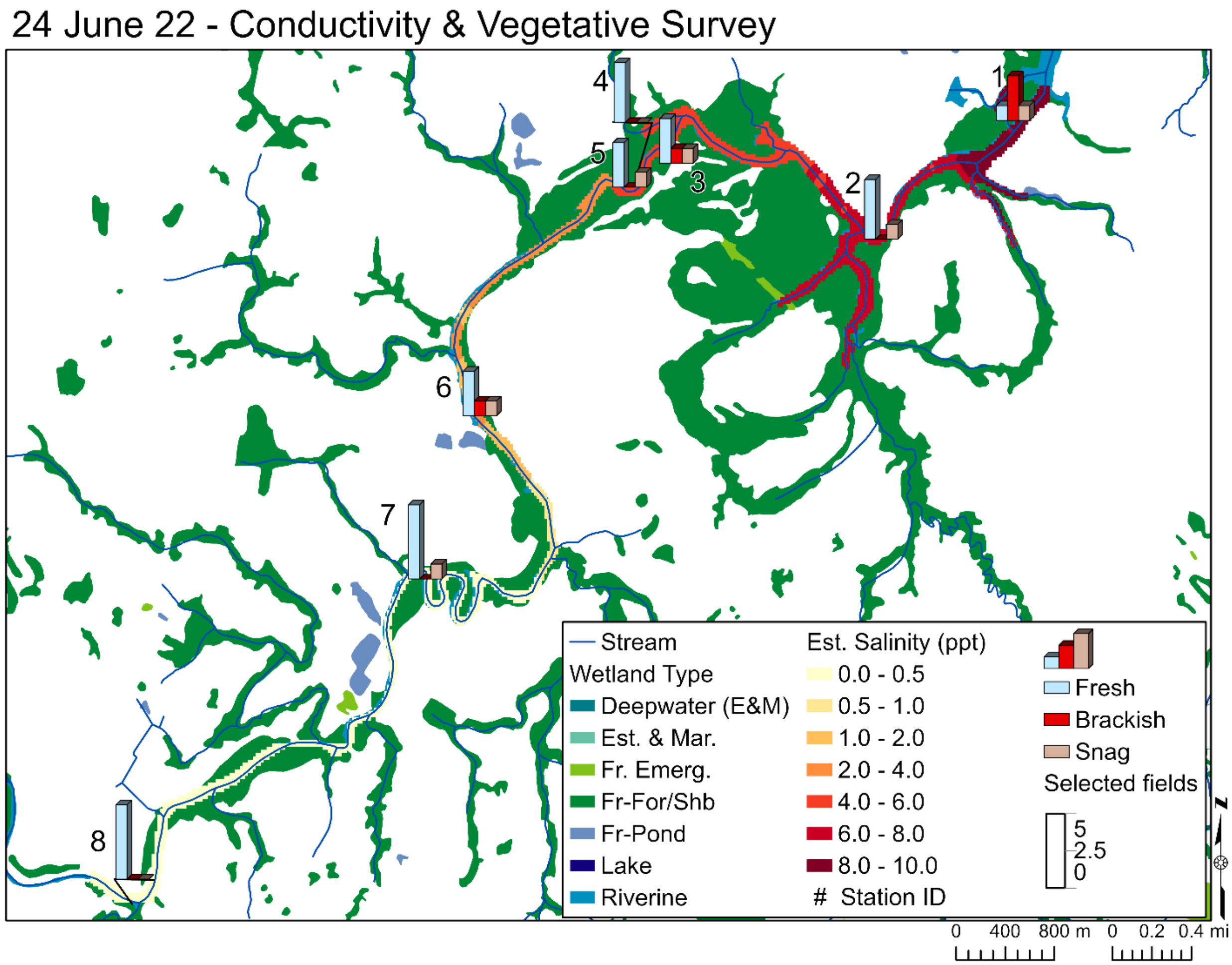


Figure 23. Map of the Lower Trent River depicting the general type of wetland class (US FWS, 2023) and estimated salinity and plant identification surveys conducted on 24 June 2022. Bar graphs show the relative number of freshwater (cyan) or brackish water tolerant species (red), or snag (brown, standing dead trees)) species enumerated during the vegetative survey. Numbers adjacent to graphs denote station identification number.

A brief survey of tree species along the Trent River was conducted on June 24, 2022. Eight shoreline sites were visited downstream from Pollocksville to River Bend (approximately 21 river kilometers). We identified tree and shrub species, marsh vegetation, and presence of snag (standing dead trees) within sites approximately 200 to 250 m^2. The survey was conducted in conjunction with measurements of conductivity along the river (Figure 23). Fifteen species were tentatively identified in the field, although there was no confirmation. Scientific names of identified species are listed in bold within Table 12. We sincerely thank Kristie Gianopulos of NC DEQ for her help and direction with wetland plant species, their habitat preference, and their brackish water tolerance. The only tree species found that preferred freshwater habitat but was brackish water tolerant was *Taxodium distichum.* Brackish water tolerance was found for shrubs and non-tree species. We counted species considered to have a freshwater habitat preference and those considered to have brackish water habitat preference for each site. The sums, along with snag presence, are shown in Figures 23 and 24. The river reach was dominated by freshwater species, except the most downstream site. Species richness of freshwater species increased upstream. The most downstream site had considerable amounts of snag and was more marsh-like. However, it sat on a peninsula and may not have truly been representative of the area.

In general, our observations are consistent with effects of salinity on wetland vegetation as one moves downstream into regions of higher salinity. The most upstream site with trees preferring freshwater habitat was where salinity within the river was between 1 and 2ppt (1.6 to 3.8 mS/cm). The salinity at the most downstream site ranged between 8 and 10 ppt (15.4 to 19.2 mS/cm). Here species with both a brackish water habitat preference and brackish water tolerance were dominant. As is seen in other sections of this report, salinity at any site within this reach varies with time. Obviously, while these results are generally consistent with threshold recommendations, more effort would be needed to determine any quantitative relationship. We stress that our results must be considered preliminary. Future efforts should include functional assessment protocols as used by NC DEQ. Such assessments would not only address the abundance of plant individual species, they would, also, address community structure and ecosystem function of sites.

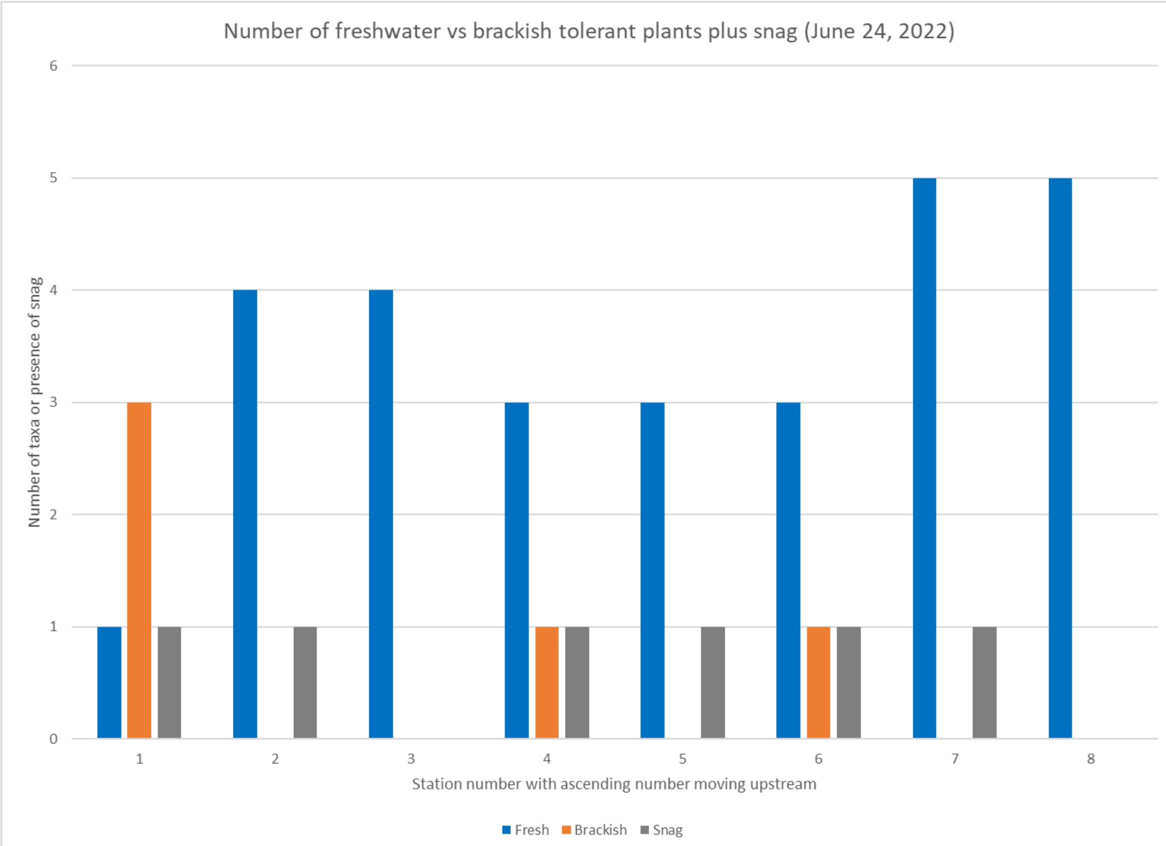


Figure 24. Number of representatives of general type of wetland plant classes with respect to preferred habitat (freshwater vs brackish water) and snag presence from survey conducted on 24 June 2022. Bars show the number of taxa preferring freshwater (cyan) or brackish water habitats (red), or snag (brown, standing dead trees). See Table 12 for classes relative to species. Numbers on X-axis denote station identification numbers.

6.6.3 Flow-Fish Community Aspects

Vegetation as an indicator for ecological flows would be expected to reflect relatively long-term salinity intrusion probably on the order of months. In contrast, fish communities are often used in assessing unidirectional flow regimes at shorter time scales. In these areas, water depth is presumed to alter habitat distribution and, hence, guild distribution and community structure. In the lower reaches of Coastal Plain rivers, salinity plays a role in fish distribution. Species have thresholds, tolerances and even dependencies for different salinity regimes during their life histories. These may be different for spawning, egg, larval, or juvenile survival compared to adult stages. In fact, fish migrations during their life may be directly linked to salinity. A summary of salinity thresholds for select, important coastal and diadromous fish species was presented in the North Carolina's Coastal Habitat Protection Plan (https://www.deq.nc.gov/about/divisions/marine-fisheries/habitat-information/coastal-habitat-protection-plan) and is shown in Figure 25. Salinity thresholds are noted that identify optimum and suitable values. Thresholds of 2 and 5 appear common, such that intrusion of salt to or above these concentrations could alter the expected fish community structure.

Note that all species listed in Figure 25 have been historically overfished and are species of interest for conservation. As a result, understanding how changes in low flow frequency and duration may affect these species has important implications for fisheries management in the state.

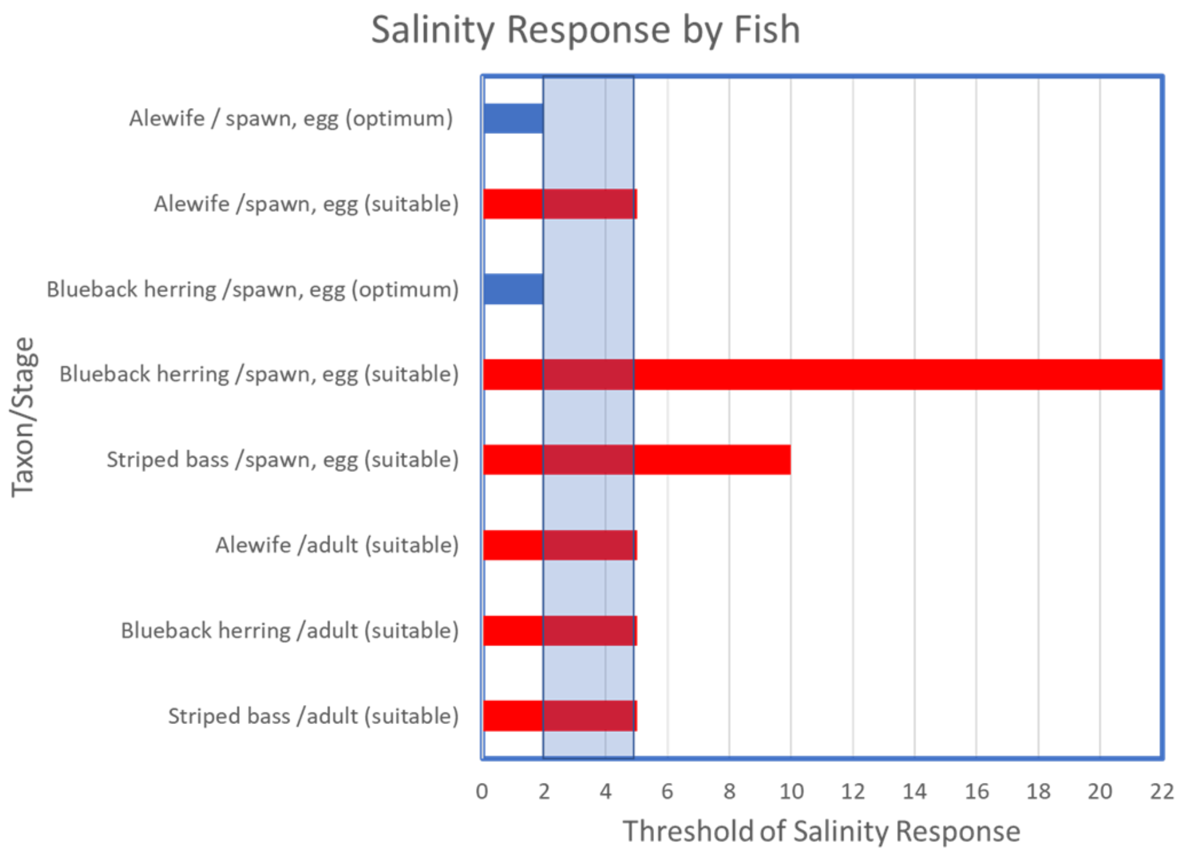


Figure 25. Salinity responses of fish species for the identification of threshold salinities for habitat range (Data from North Carolina's Coastal Habitat Protection Plan (2021). Thresholds relate to either habitat for spawning and egg development of adult growth, behavior and survival. Lower threshold of 2 ppt estimates consensus upper region of optimum conditions. Upper threshold of 5 ppt provides an estimate of consensus salinity of upper region of suitable conditions.

Assessing salinity effects on fish communities based on fisheries independent data is challenging in North Carolina because different sampling designs are used by the NC Wildlife Resources Commission (NCWRC) and the NC Division of Marine Fisheries (NCDMF), making it difficult to compare results across surveys. Electrofishing is the primary survey technique used by NCWRC. This method becomes less efficient at surveying fish as salinity rises. Based on a consultation with fisheries biologists from NCWRC, their surveys are often curtailed once salinities reach 2-3 ppt due to this issue. These salinities are fresher than those typically surveyed by NCDMF. Thus, there is a gap where little information on NC fish communities is available, which coincides with the zone where rivers might experience salinization during low flow events.

While it was beyond the scope of our current project to survey the fish community on the Trent River, we obtained baseline data for this river from two electrofishing surveys conducted by NCWRC in 2014 and 2022. In 2014, the Trent River was surveyed during May, June, October and November, whereas in 2022 the survey took place during October and November. Collectively, 17 species were identified during these two surveys, with eight species constituting 95% of the catch. These eight species included Bluegill, Largemouth Bass, Redear Sunfish, Pumpkinseed, Bowfin, Yellow Perch, Redbreast Sunfish, and Chain Pickerel. Overall, 10 of the species collected occur solely in freshwater, four species occur in both freshwater and brackish habitats, and three species were diadromous (e.g., Gizzard Shad, American Eel, Striped Mullet), with changing salinity requirements across life history stages.

A notable change in salinity was observed between the 2014 and 2022 surveys. Mean salinity was 0.7 ppt in 2014, ranging from 0.1-3.2 ppt. In contrast, salinity was higher in 2022, with a mean of 3.5 ppt and a range of 0.1-10.6 ppt. This difference may in part be due to the 2022 survey taking place during a drought (mean/min. discharge was 46/12 cfs for Oct-Nov. 2014 and 36/6 cfs for Oct.-Nov. 2022). Also, it should be noted that there were several missing records of salinity in 2014.

We examined the five stations sampled by NCWRC in 2022 with the highest salinities (Stations Bryce 1, FDitch1, Lawsons Creek, NR-Trent4, and OldTown1) to see if their species composition was atypical. Qualitatively, two of these stations had low species richness with only one fish species present (e.g., Largemouth Bass). Two other stations had high abundance of pumpkinseed, which is a species that occurs in both freshwater and brackish habitats. The fifth station with high salinity exhibited species richness and abundance patterns that were typical of other sites surveyed. Additional quantitative analysis and surveys are needed to determine if salinization of the Trent River and low flow events may affect fish abundance, species composition, and biodiversity. Such surveys should target larval or juvenile fishes, as well as adults, since early life history stages often have different salinity tolerances.

Of course, salinity is not the only factor affecting fish communities. Water quality, including dissolved oxygen (DO) concentrations and temperatures, can be an important determinant of community structure. In some cases, there may be interactions between multiple stressors affecting fish communities. For example, changes in one aspect of water quality, such as salinity, DO, or pH, can affect the bioenergetic budget of fishes decreasing energy available for other activities. For example, stressors that lead to a greater need for regulation of an organism's internal osmotic or pH balance reduce the aerobic scope of fishes or invertebrates, which can then lead greater sensitivity to thermal stressors (Portner and Farrell, 2008).

Also, ecological interactions among species can be important. One challenge related to determining whether salinization and low flow may be affecting fishes on the Trent River is that invasive Flathead and Blue Catfish have altered species composition in recent years, resulting in a shifting baseline. Although their diet is diverse, these fishes can be piscivorous and may alter the abundance of native fishes in both freshwater and estuarine habitats. This invasion became pervasive in the Virginia sector of Chesapeake Bay a few years before the invasion of North Carolina waters. In the Chesapeake Bay, there is concern that Blue Catfish is negatively impacting populations of commercially important species, such as Shad, Menhaden, and Blue Crabs. Similar impacts are anticipated in North Carolina. Fish community and stakeholder surveys may help to shed light on these challenges in the future. Initial efforts to engage stakeholders and gain an understanding of their perspectives on the broader topic of environmental flows are discussed in the next section.

6.7 Stakeholder Perspectives

6.7.1 Introduction

The significance of ensuring that all participants in environmental processes are aware of the problems, the diversity of viewpoints and opinions, and the benefits and costs of decisions and policies are becoming increasingly evident (O'Keeffe, 2019). In most countries, freshwater management and estuarine management have grown into separate programs with independent objectives, authorities, policies, and institutional structures (Olsen, 2006). However, by combining key elements of integrated coastal management with integrated water resources management, researchers have developed a comprehensive set of guidelines that address the need to integrate river and watershed management with estuary management, placing specific emphasis on the role of stakeholders in this process (Olsen, 2006). Currently, the National Estuary Program and the Albemarle Pamlico National Estuary Partnership are attempting to integrate watershed (freshwater) management with estuary management. Entities that have, or may have, an impact on a decision are referred to as stakeholders. Stakeholder integration degrees in participatory techniques vary depending on the approach's objective. Due to the growing complexity of water resource challenges and the urgent need for coordinated responses across diverse stakeholders, including agencies, organizations, and individual land managers, collaborative initiatives to water resource management, including stakeholder engagement, are on the rise (Burbach, 2013). Discussion and negotiation result in social engagement and the acquisition of new information to support change (O'Donnell, 2018). High-quality stakeholder participation is necessary for effective collaborative resource management. Stakeholder engagement is a process where participants—those who are directly or indirectly impacted by and able to influence a decision—take an active involvement in the research, planning, and policy decisions that have an impact on their lives (Burbach, 2013).

Stakeholder engagement is the purposeful participation of stakeholder groups that have been identified and who have a stake in the success of environmental flow management. Involvement can range from superficial, including just information sharing and dialogue, to deeper engagement and collaborative governance (Mussehl, 2022). Collaboration across a wide range of stakeholder groups, including landowners, scientists, and legislators, is necessary for water-related developments or adjustments and provides possibilities for social contact, relationship development, and training that might encourage creative thinking and collaboration in response to complicated water resource concerns (O’Sullivan, 2020; Burbach, 2013). According to this concept, decision-making includes discussion and collaboration between stakeholders from the public, nonprofit, and private sectors (Margerum and Robinson, 2015). The benefits of collaboration for procedures and results have been emphasized to make it possible for people to participate in environmental decision-making. These advantages include the collaboration of stakeholders' efforts to support more effective and responsive management, the inclusion of a wide range of perspectives to guide decision-making, conflict management, the improved performance of social and institutional capacity to address complex water management challenges, and the transformation and integration of knowledge (Margerum and Robinson, 2015). Participation of stakeholders can contribute to reducing the transaction costs related to environmental flow programs in river systems, which may be important in highly unique ecosystems. Engagement of stakeholders may also lessen the requirement to minimize uncertainty before a program can commence, improving productivity. It is generally believed that stakeholders who trust a program and feel engaged are more likely to cope with greater risks and levels of uncertainty; hence their willingness to accept might be higher (Conallin, 2018).

Environmental flow program implementation is frequently hindered by considerable social and political issues, according to experts (Harwood et al., 2018; Horne, 2017, Mussehl, 2022). These issues include poor stakeholder participation, a lack of broader public support, and political reticence. As a result, requests have been made to increase stakeholder participation in the environmental flow assessment process, extending the different perspectives represented and representing the values of communities within a waterbody (Mussehl, 2022). One of the challenges in this path is that it could appear difficult to explain the concept of environmental flows to stakeholders who may be unfamiliar with the topic. While most people would agree that rivers are important sources of freshwater for life, livelihoods, food production, industry, and sanitation, those uses can come in conflict with environmental needs. As a result of this conflict, water that flows in a river, particularly during times of drought, may be seen as a missed chance to enhance human well-being, if not as a waste. Therefore, it takes a cognitive shift to accept the assumption of environmental flows, which asserts that water should be left in streams and that, to maintain reasonably acceptable environmental conditions, rivers may need to retain a significant amount of mean annual runoff (O'Keeffe, 2019).

Engagement programs should be envisioned as long-term initiatives that regularly reengage participants, recruit new participants, and are sufficiently self-reflective to capture shifting perceptions and interpersonal dynamics (Mussehl, 2022). Individual stakeholders have varying opinions and understandings about the issues and other stakeholders at the beginning of a new engagement process. Therefore, examining cognitive transformation at the group level requires evaluating whether debate, deliberation, and learning loops affect people's viewpoints, as well as how much those new perspectives merge into a coherent vision (Eaton, 2021). To achieve procedural and equitable justice, some researchers contend that natural resource management organizations must not only effectively involve stakeholders in the decision-making processes but also allow the variety of stakeholders' needs and viewpoints to have an impact on the result. However, participation in water planning may not always achieve its goals. It also occasionally leads to conflict when strongly held beliefs prevent other stakeholder groups from being heard or having the same degree of control over the process. It is evident that some groups continue to be at a disadvantage in such procedures, even though such engagement experiments frequently serve as effective vehicles for input from significant water users (Lukasiewicz, 2017).

Participating members of the community should be able to represent broader ideas and viewpoints held by the community while also contributing unique local expertise to the decision-making process (Mussehl, 2022). It is important to reach an agreement on water allocation for the environment with opposing stakeholder groups that have various perceptions and priorities (O'Sullivan, 2020). Therefore, people need to be educated by persuasive arguments as to why the change is valuable and desired. Although the economic benefit of consumptive water uses, which many general stakeholders are aware of, must compete with the scientific process of assessing water demands to maintain biophysical diversity and processes, it may seem convincing to specialized environmentalists. The understanding and social acceptance of environmental flows will advance significantly once it is demonstrated that the scientific indicators are associated with the preservation of a wide range of products, services, and livelihoods that stakeholders highly value (O'Keeffe, 2019). Overall, it is important to build up decision-making procedures that allow interested parties to participate and influence the decisions that are made (Borisova, 2012).

6.7.2 Purpose

The creation and implementation of water management policies may be impeded by the lack of consideration given to stakeholder opinions and preferences during the decision-making process, as this may foster mistrust in governance systems (Britton, 2021). Assessing the costs and benefits of ecosystem change, as well as allocating costs and benefits among stakeholders, remains challenging. This is especially true for estuary systems, which are frequently impacted by arbitrary choices that alter the flow and quality of the water (Olsen, 2006). The participation of local stakeholders can contribute useful local knowledge, increase the effectiveness of interventions by accounting for local conditions, facilitate compromises and cooperation among diverse stakeholders, meet the needs and expectations of local stakeholders, aiding in the implementation of decisions by instilling local support, and enabling social learning (Lukasiewicz, 2017). The extent to which water stakeholders are satisfied with how water is being distributed and managed directly relates to the degree of sustainability attained. The only method for achieving a high level of satisfaction in water management is to promote an accessible, fair, and transparent stakeholder dialogue that allows all water interests to be acknowledged and yields water allocation decisions that are viewed as fair and equitable by those stakeholders (Richter, 2010).

The purpose of this survey was to determine stakeholder preferences and perceptions of ecological flow conditions in Eastern North Carolina, as well as stakeholder recommendations for policies and guidelines to promote ecological flows. We distributed a 20-question survey using Qualtrics. Our aim was to find out how stakeholders thought regarding ecological flow requirements, in addition to related issues such as low flows, declining flows, droughts, and other changes in ecology and hydrology, and their preferences for potential and hypothetical scenarios related to guidance and policies on how to approach low and declining flows.

6.7.3 Methods

The survey was conducted from October 2021 to February 2022. Survey respondents were largely residents of the Tar and Neuse River basins in eastern North Carolina (Figure 26). Most of the survey distribution was carried out in person at public meetings and farmers' markets, with some modest internet distribution via email listservs. We designed questions to gain a better understanding of stakeholder perceptions regarding what was causing the low flows in eastern North Carolina. Stakeholders were questioned on the extent to which the following variables cause low flows: water usage from various industries, an increase in drought, poor mismanagement at the state or local level, or a combination of these variables or other causes. To address the policy aspect of the problem, other questions were devised that posed a hypothetical drought scenario and asked respondents to identify strategies for dealing with the crisis. The poll received responses from 77 individuals. Results were delineated according to geography and hydrology to see whether there are any variations between people who live in rural and urban areas, in addition to determining if they live close to the coast or if they live further inland. Questions covered subjects such as demographics, perceptions and concerns, policy preferences, preference for action, and perception of change.

6.7.4 Study Area

The respondents were largely from Trenton, Greenville, Washington, and New Bern, with a minor number also hailing from other nearby communities (Figure 26).

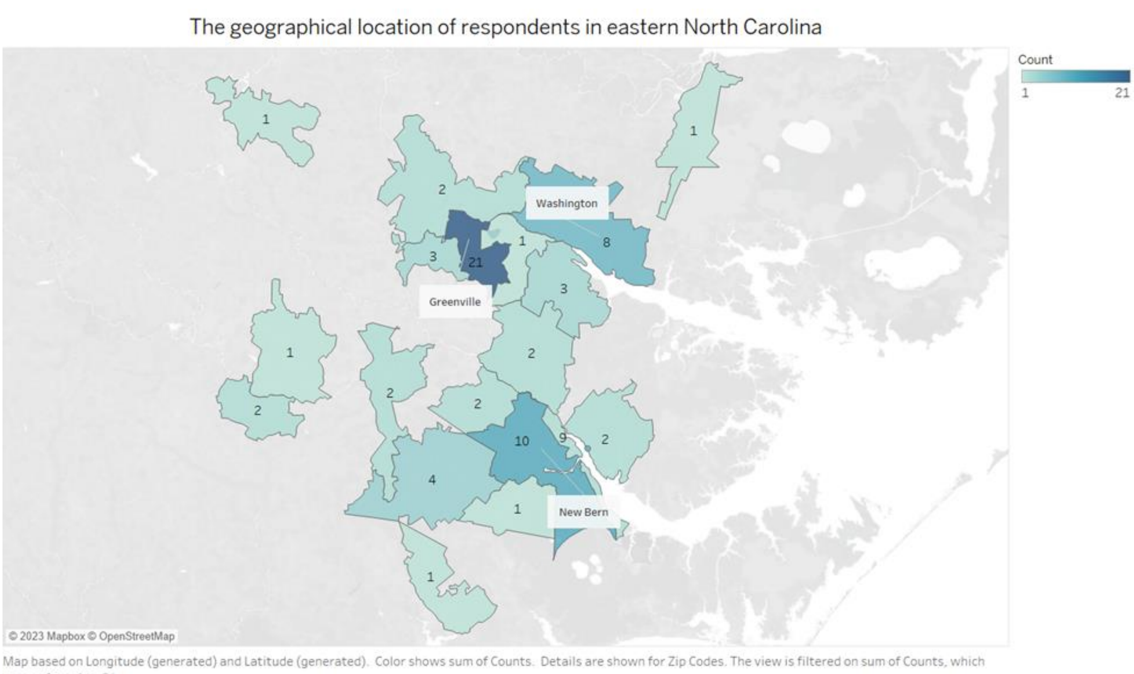


Figure 26. The geographic location of respondents

6.7.5 Results

Stakeholders' Perceptions

The findings demonstrate clearly how stakeholders responded to the questions about their perspectives on the problem and their concerns. According to the majority of respondents (Figure 27), the main reasons for low flows in eastern North Carolina include overuse of water by industry, an increase in drought or less rain over time, overuse of water for agriculture, and poor management. However, unsurprisingly, water quality, floods, and low flows were respondents' top concerns regarding the future of water in eastern North Carolina.

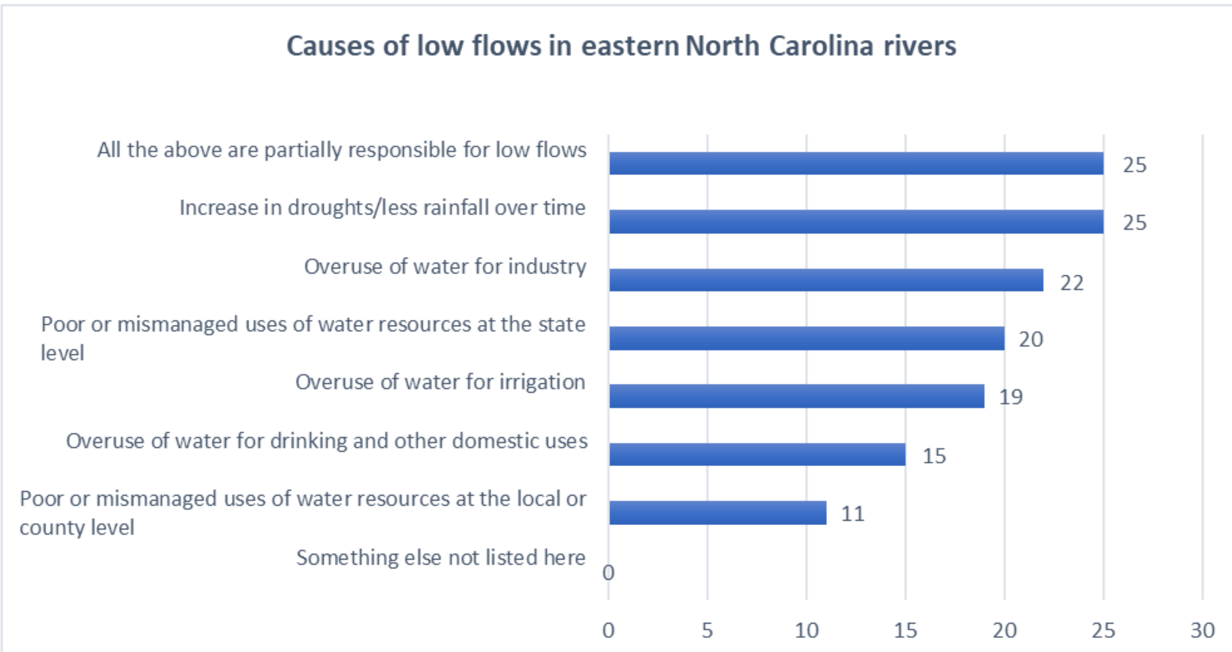
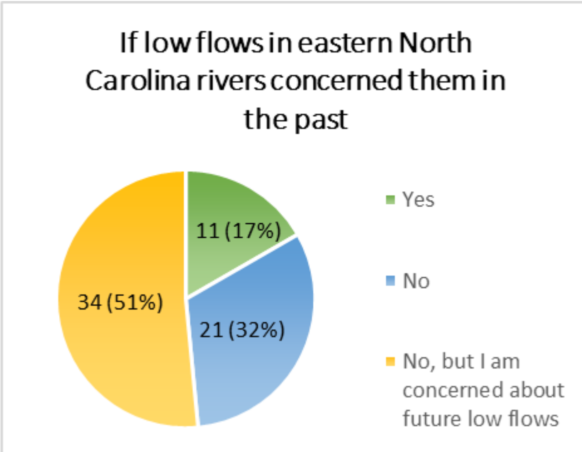


Figure 27. Causes of low flows in eastern North Carolina rivers

Respondents were asked if they had previously expressed concerns about the drought and low flows in Eastern North Carolina. It was discovered that less than one-third of the respondents were not concerned regarding either of the issues, but are more concerned now, even though the number of respondents concerned about low flows was lower than the number of people concerned about drought (Figure 28).



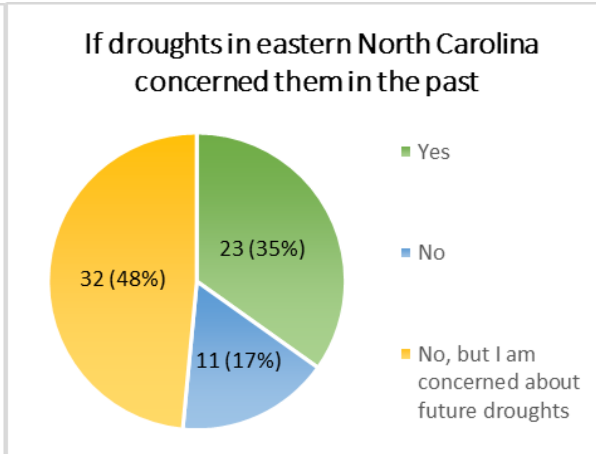


Figure 28. Concerns regarding low flow and drought in the past

When asked how the respondents and their neighbors had coped with drought in the past, most respondents indicated that they had both used less water and practiced water conservation, though their neighbors had not done so concurrently (Figure 29).

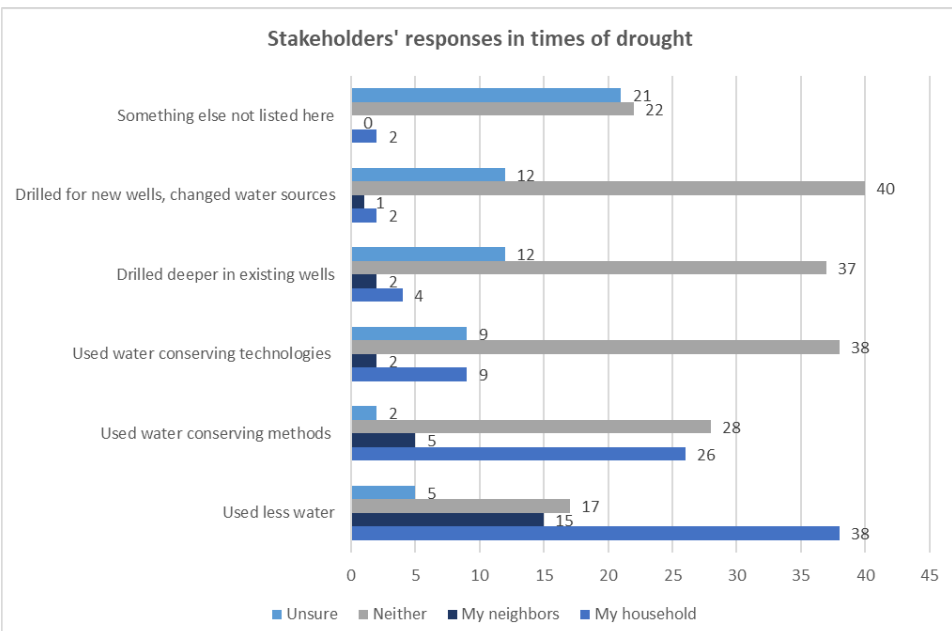


Figure 29. How stakeholders have responded in times of drought.

Stakeholders were asked to identify the most concerning factor for the future of water in eastern North Carolina. River water quality, floods, and drinking water quality were the factors that the respondents found to be most worrying, followed by low flows and drought (Figure 30).

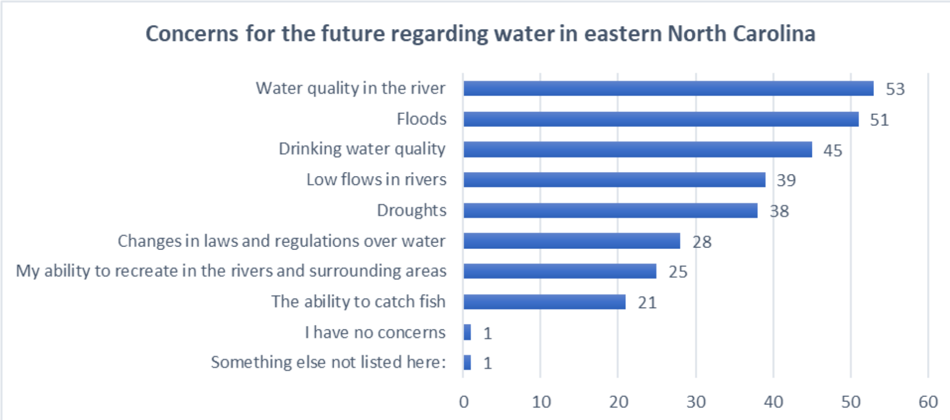


Figure 30. Concerns for the future regarding water in eastern North Carolina

Policy Preferences

Stakeholders were inquired about the policies stakeholders would support in response to hypothetical scenarios concerning their preferred approach to water management issues. Stakeholders were more in favor of measures like mandating water meters for users who use more than 10,000 gallons of water per day or granting water permits in periods of drought to these users. They were less in favor of establishing permanent water permits for large users who use more than 100,000 gallons per day (Figure 31). The preferred public engagement approach was notification of policy changes, but interest was also expressed in various levels of involvement (Figure 32).

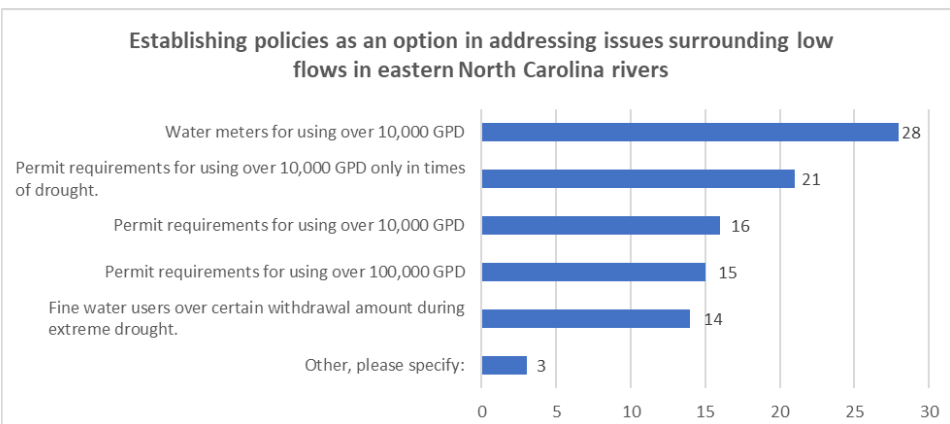


Figure 31. In terms of public engagement in resolving concerns regarding low flows in eastern North Carolina, respondents did not exhibit strong preferences between the three given selections.

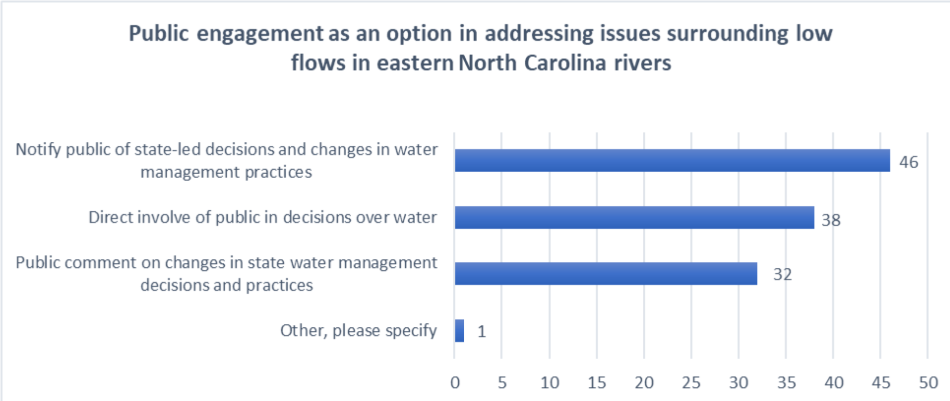


Figure 32. Public engagement for addressing issues surrounding low flows in eastern North Carolina rivers.

Additionally, in terms of financial incentives for water management, state subsidies, and tax breaks were preferred over volunteer compensation for decreasing water use and improving water efficiency (Figure 33).

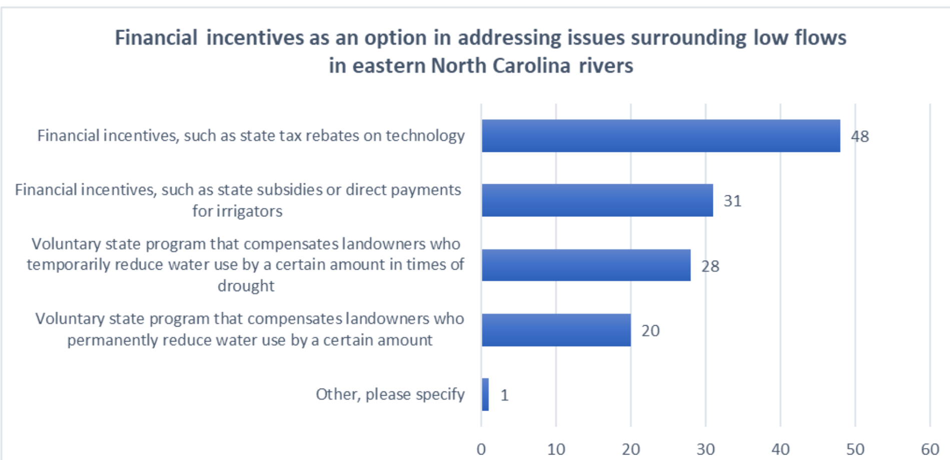


Figure 33. Financial incentives for addressing issues surrounding low flows in eastern North Carolina rivers.

Preference for Action

The survey also included questions presenting hypothetical scenarios where respondents were asked about their preferred course of action for these scenarios. One of the questions presented a scenario where respondents selected preferences for which actions should be taken against a polluter who directly discharges undiluted wastewater into the river. Respondents were more likely to advocate for more preventative actions like expanding the capacity of wastewater treatment or storage as opposed to having the polluter pay (Figure 34).

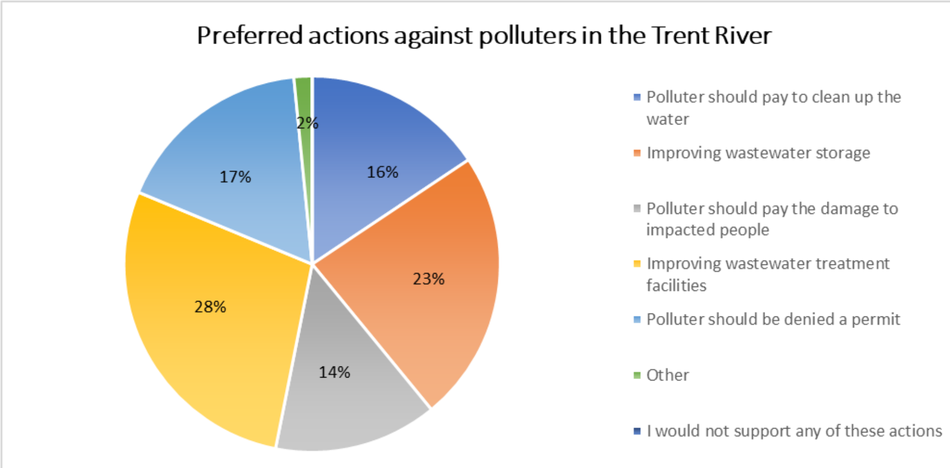


Figure 34. Preferred actions against polluters.

The second scenario question, which discussed drought situations and preferred course of action, demonstrated that respondents preferred preventative approaches over more top-down policies, such as limiting water use for commercial or merely public use (Figure 35).

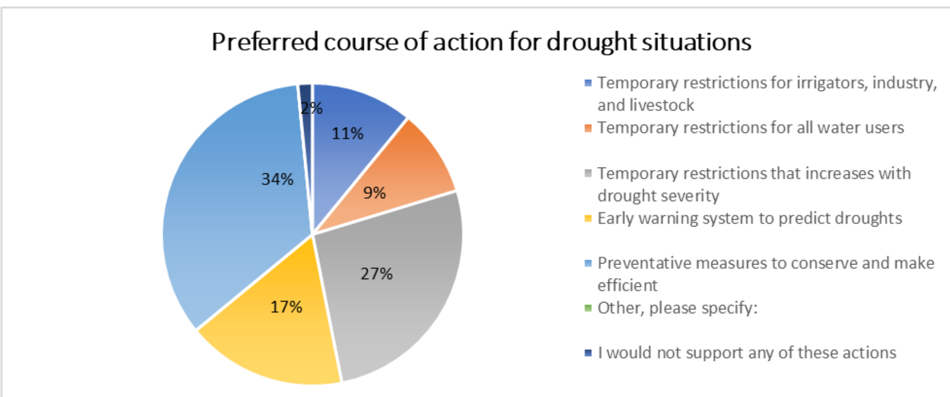
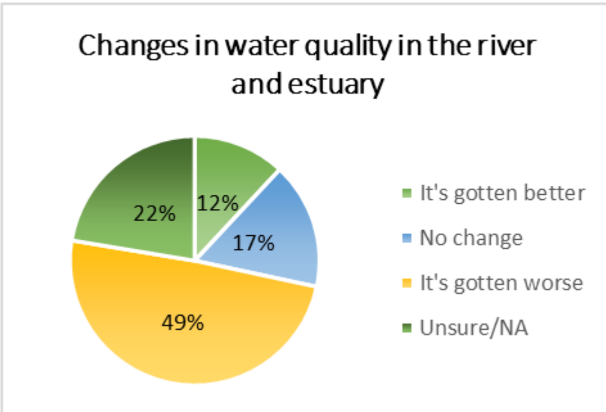


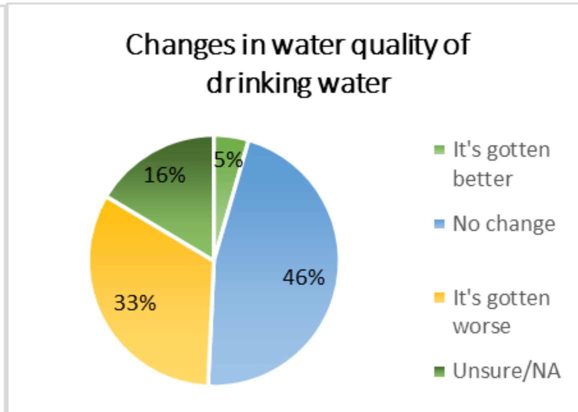
Figure 35. Preferred course of action for drought situations.

Perception of Change

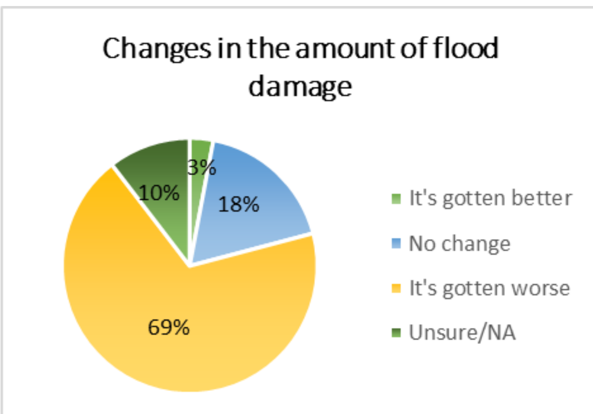
As a further inquiry into stakeholders' perceptions of change, respondents were asked about how they perceived changes in different hydrologic and ecological circumstances over time in the last 10 to 20 years. Thus, they were asked as to whether they had observed or experienced changes in the ecology, drought, and the duration and frequency of floods in eastern North Carolina. The majority of respondents had noticed changes in the ecology, the frequency of floods, and the length of floods in the last 10 to 20 years. Additionally, respondents thought that the number and length of droughts either remained the same or increased (Figures 36 and 37).

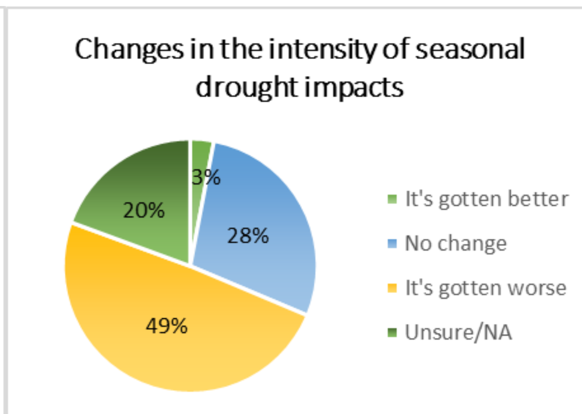


a (11)



b (11)

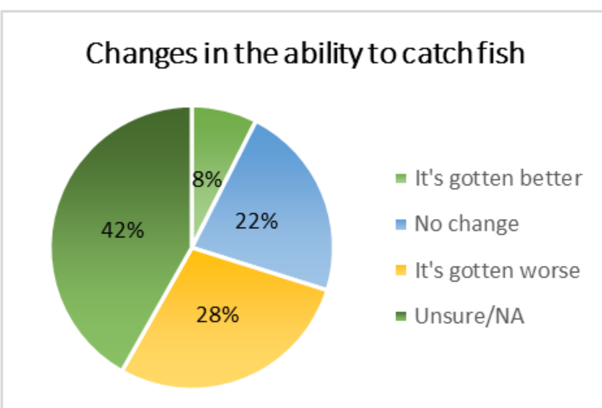




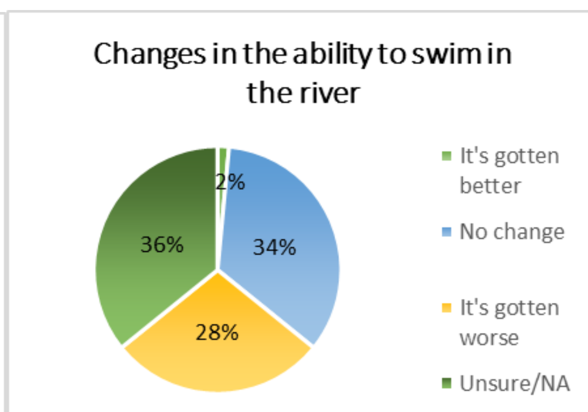
c

(11)

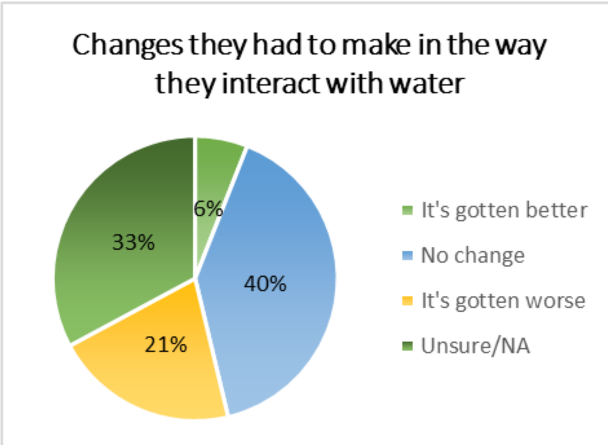
d (11)

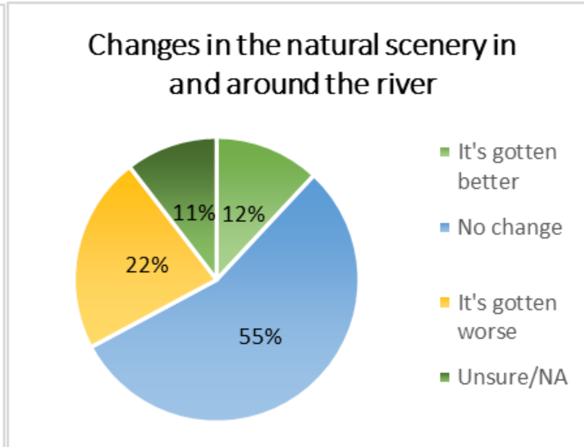


e (11)



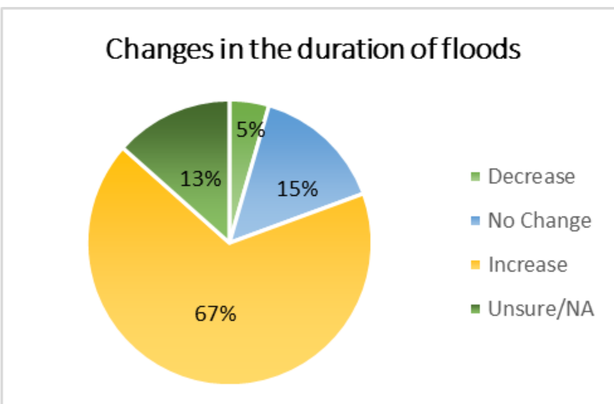
f (11)

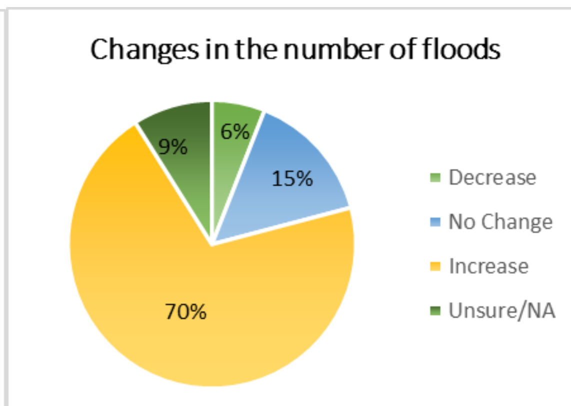




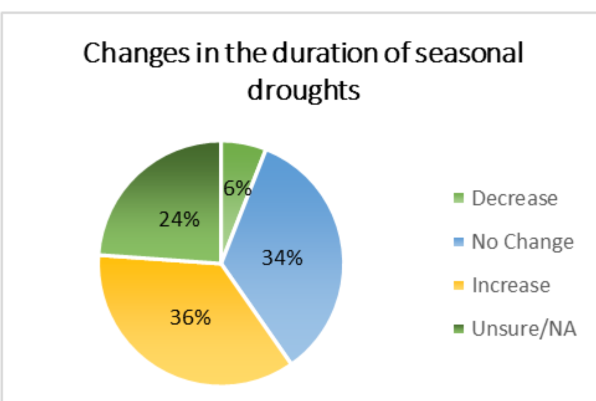
g (11) h (11)

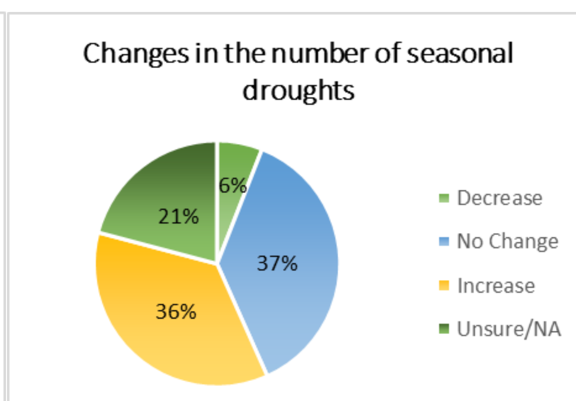
Figure 36. Stakeholders' perceived changes in the following categories over the last 10 to 20 years in eastern North Carolina



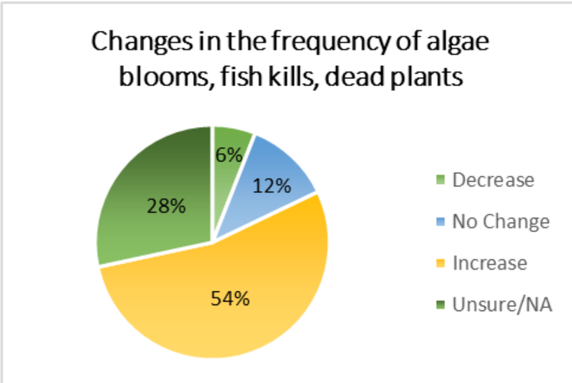


a (12) b (12)





c (12) d (12)



e (12)

Figure 37. The observed changes in the following categories over the last 10 to 20 years in eastern North Carolina.

As previously noted, to determine whether there were any changes in the respondents' answers based on where they resided (further upstream vs. downstream), the respondents were divided based on their reported zip code into groups according to whether they were closer to the estuary or further inland. There were no geographic disparities in responses to questions except for the question on the causes of the low flows. Comparing their responses to those of their coastal counterparts, participants who resided further inland were more likely to believe that excessive domestic water usage and an increase in drought were the main causes of low flows in eastern North Carolina. As previously mentioned, the observations of water levels along the Trent revealed that drought influence on water levels was more visible inland when compared to tidal reaches, it is possible that this may relate to differences in perception of drought influences on surface waters based on watershed location. Overall, the survey findings can help to guide potential future policy and management. Potential approaches will be discussed in the next section.

7. Conclusions and Recommendations for Future Research and Policy Development

7.1 Hydrologic Considerations

Findings along the Trent River and from an extensive literature review suggest that low flows can have different influences on ecosystem processes depending on location within coastal watersheds. In the upland sections of the Trent River (upstream of tidal influence) low flows will correspond with low stages; the influence of low flows can cause a decrease in aquatic habitat and connectivity as water level decreases. Ecological flows along reaches upstream of the tidal extent can be assessed by the methods described by the EFSAB (2013). In areas downstream of Trenton (tidal reaches), as the river approaches sea level and the channel widens, declining flows during low flow periods tended to have a lesser influence on water levels. Tides and wind dominate control of water level during low flow periods. Therefore, the decline in habitat extent due to declining stage with low flows may have less of an impact in the portions of the watershed closer to sea level. In addition, there was evidence at Pollocksville that sea level rise is causing the river level to rise over time. One of the main consequences of low flows in the lower portion of the Trent River was the occurrence of saltwater intrusion inland during low flow periods. This is an important consideration for ecological flow management in these settings because the frequency, duration, and concentration of saltwater incursions influence the ecological impacts. Salinity and flooding impacts of low riverine flows to wetlands within lower rivers are intertwined with those of sea-level rise. Thus, any target reference conditions for ecological flows need to accommodate projected sea-level rise (Christian et al. 2000). High salinities can affect the movement of aquatic organisms, reduce suitable habitat and alter species distributions and competition, as well as create stress for the adjacent vegetation communities. Therefore, the relationship between low flows and inland salinity migration is a key aspect of ecological flows in these settings. A key question is: what is an acceptable salinity level (inland extent, duration, frequency, seasonality) to support ecological integrity? As droughts exacerbate low flows, this question is particularly important at these times.

For the Trent, as in many Coastal Plain watersheds, the primary public water supplies are obtained via groundwater wells. It was beyond the scope of this study to perform a detailed analysis of the influence of groundwater withdrawals on baseflow in the Trent River, however additional information on water supply and water use is provided in Appendix B. Due to the proximity of groundwater supply wells to the Trent River, there is a possibility that these withdrawals may influence flows. In turn base flows that allow saltwater intrusion may affect potability of well water. A more detailed analysis is called for.

Earlier work by the NC EFSAB (NC DEQ 2016) recommended "to establish ecological flows on the basis of 80–90% flow-by (i.e., 80–90% of ambient modeled flow remains in the stream) in combination with a critical low flow component that identifies when additional actions may be needed to protect ecological integrity. The critical low flow component is intended to minimize increases in the magnitude and duration of extreme low flows during drought conditions. If the basinwide hydrologic models and critical low flow component indicate that there is not sufficient water available to meet essential water uses and ecological flows at a given location, further review by DEQ is recommended. The EFSAB did not recommend a specific value for the low flow component but recommended that DEQ establish these values based on an analysis of typical and extreme low flow conditions in North Carolina." To build on this work and account for the differences in coastal and estuarine systems, additional efforts to evaluate flow-salinity relationships in the riverine-estuarine transition zone are called for to develop critical low flow guidance for rivers discharging to the Albemarle-Pamlico estuarine system. Based on watershed area, slope, and previous work by USGS (Giese et al. 1985), there is evidence that the Tar and Neuse Rivers have similar flow-salinity relationships as were observed in the Trent. In addition, smaller river systems where the channel elevation is close to sea level, there may be little change in flow-stage relationship throughout the watershed, in those cases the flow-salinity relationships may be most important for consideration.

With respect to the low flow influences on inland migration of salinity, there are additional aspects that are of societal importance, such as the impacts on potable freshwater supplies and agricultural productivity. For example, similar patterns of increased salinity during low flow conditions were observed along the Tar River, with evidence of periodic saltwater intrusion during droughts observed at the Grimesland, NC DEQ ambient monitoring station (approximately 6 miles/10 km upstream of the Pamlico River estuary at Washington) and at the Streets Ferry monitoring location along the Neuse River (approximately 6 miles/10 km inland). Greenville is the only city with a run-of-river public water supply in the region. The vulnerability of its water supply to inland saltwater intrusion during extreme low flows and with sea level rise needs evaluation. Other towns and farms along the tidal river reaches of APES, also, need assessment.

7.2 Ecological Considerations within Lower Coastal Plain Rivers

We considered several options for indicators in ecological flow assessments. In its 2013 report to the NC Department of Environment and Natural Resources (renamed NC Department of Environmental Quality in 2015), the EFSAB recommended that the biodiversity of macroinvertebrate fauna and fish be used as an indicator of whether declines in ecological flows were having deleterious effects on aquatic ecosystems in gaged rivers. In tidal regions, we suggest that other modes of assessment may be needed. Wetland plant communities serve as indicators for long-term (month or more) low flows. These communities are addressed through functional assessment tools, such as those used by NC DEQ (Wetland Project Summaries (NC DWR) : North Carolina Wetlands (ncwetlands.org)). Importantly, as these tools address community condition; they also address other ecosystem characteristics and provide assessment of ecosystem functions and, hence, ecosystem services. The functional assessment approach would provide a better understanding of broader ecological condition than simply community structure. A monitoring program of functional assessment of vulnerable wetlands in the Lower Coastal Plain would provide a baseline for long-term planning that includes ecological flows.

If salinity effects on wetland vegetation are to be used in establishing ecological flows, the very nature of salinity needs addressing. There are temporal and spatial considerations in linking surface water salinity to soil salinity. Vegetation response may be dependent on both flooding of surface water and penetration into the soil. Also, methods of measurement and units of analysis can differ for soil and surface water (see Anderson et al. 2022 as an example). An assessment of these relationships needs to be done to more accurately link flow, salinity and wetland vegetation response.

Faunal communities represent targets for ecological flow assessment that could be used in the tidal region. Fish communities may be a challenge to use as indicators because of methodological issues near the freshwater/saltwater interface and invasive species. Strong coordination between WRC and DMF is needed to develop protocols for such assessments. Even if the methodological problems are overcome, a response signal from salinity may be weak compared to those of invasive species, fishing pressure and other water quality parameters.

Benthic macroinvertebrates have been shown to be useful for assessing impacts of changing ecological flows in the Piedmont and Mountains regions of North Carolina, but their utility in the Lower Coastal Plain requires further evaluation. This is because many estuarine systems exhibit complex biodiversity patterns in areas where there is mixing between freshwater, brackish, and marine taxa (Kaiser et al., 2011). Some taxa exhibit a biodiversity minimum at salinities of 5-8 since the abrupt transition between marine and freshwater conditions can be physiologically stressful, while other taxa exhibit maximal biodiversity in this region (Kaiser et al., 2011; Telesh et al., 2013). Also, beta-diversity, which is related to turnover of species composition at the landscape level, is maximized in such estuarine settings (Kaiser et al., 2011). Since low flow events and associated salinization can change the location of the interface between freshwater, oligohaline, and mesohaline habitats, low flows could lead to increases or decreases in biodiversity in some areas due to intermixing between faunal assemblages with different salinity tolerances. In cases where species richness increases due to such intermixing, an indicator based on biodiversity alone may lead to mistaken conclusions about the effects of low flows on the ecological integrity of Coastal Plain habitats. Consequently, alternative ecological indicators are needed for the Lower Coastal Plain. Earlier work by Eaton (2001) provides guidance for utilizing benthic macroinvertebrate indices to evaluate water quality in North Carolina estuarine settings. These approaches have been utilized in Florida and are worthy of further consideration (Palmer et al. 2015).

An alternative approach would be to use a suite of indicator species to assess the ecological consequences of low flow. Among the fish fauna of the Trent River surveyed by the 2014 and 2022 NCWRC sportfish surveys, an ideal indicator species was not identified because the species that utilized brackish habitats either were diadromous or also occurred in freshwater habitats. As a result, they are expected to be widely dispersed along the river regardless of salinity. Previous research described earlier in this report (Kennedy and Barbier, 2016; Doering and Wan, 2017) suggests that blue crab might be a good indicator of changes in flows given their sensitivity to salinity. Changes in fishes and mobile invertebrates, such as blue crab, might be useful indicators of transient changes associated with salinization pules events; however, sessile invertebrate species may be better indicators of changes taking place at the time scale of weeks to months. Barnacle species have been shown to be useful indicators of salinization in other areas given that different taxa have specific salinity tolerance ranges (Poirrier and Partridge, 1979; McPherson et al., 1984; Dineen and Hines, 1994; Wrange et al., 2014). Since barnacles colonize free-floating docks and other man-made structures, they could serve as an ideal taxon for tracking salinization events via the use of citizen science. Similarly, freshwater mussels, including several species that are endangered and of conservation interest, might be indicators that a Coastal Plain river reach has not been exposed to salinization due to low flow events. Previous work by NC Museum of Natural Sciences has identified 12 mussel species in the Trent River, but no concurrent salinity data are available to assess the local tolerances of these species. Lastly, when developing indicator species, distinct life history stages should be considered. Early life history stages of fishes and invertebrates often have a narrower tolerance range of many types of environmental conditions (Kroeker et al., 2013; Wenger et al., 2017; Dahlke et al., 2020), including salinity. Also, juvenile fishes are less mobile than adults so they may not be able to avoid salinization events by moving to alternative habitats.

As discussed earlier in this report, there is a spatial gap in between surveys of freshwater and marine habitats surveyed by NCWRC and NCDMF, respectively. This gap coincides with locations that are most likely to be impacted by salinization during low flow events. If funding were available in the future, it would be good to fill this gap to create spatially contiguous indices of fish abundance to analyze how changes in flow may impact ecological communities. However, even if this gap could be bridged, challenges might exist comparing different gear types used by NCWRC and NCDMF. Electrofishing used in NCWRC surveys becomes less efficient in brackish waters and is not feasible in estuarine or marine habitats. Similarly, trawl surveys, which are used by NCDMF, can be difficult to conduct in many rivers since gear can become hung up and/or damaged by submerged tree stumps or other debris. Beach seines, another gear type frequently used in estuarine surveys of fishery resources, cannot be used as efficiently in locations with deeper riverbeds. Gill nets could be a useful gear type for surveying fish fauna diversity across freshwater and estuarine habitats since it can be used in both environments.

Another challenge related to development of indicators of Coastal Plain low flows is that the inland saltwater incursion events often occur as pulses. They appear to be more likely when conditions coincide with the following: elevated estuarine salinity, low river flows, and strong winds blowing in the upstream direction along the river channel. Eventually we would hope to develop a predictive framework to forecast or nowcast salinization events. However, until such predictions are developed, it may be difficult to organize surveys so that they occur synchronously with low flow events. Consequently, we recommend that future research on the ecological impacts of low flow take a space-for-time approach. Montagna et al. discussed a similar approach for evaluating Texas estuaries across a salinity gradient (2021). This approach would survey a complete expanse of habitats from freshwater to fully estuarine environments. Changes in isohalines would be tracked by river mile and the spatial distribution of the corresponding biotic community could be compared with shifts in isohaline position. This approach would allow for tracking shifts in fish and invertebrate assemblages across salinity gradients and the identification of candidate indicator species.

Based on the potential impacts that low flows can have on ecological integrity, there is a growing need to develop policy that can protect the ecosystems of tidal rivers and estuaries from the impacts of water withdrawals on extreme low flows. The initial efforts in this study to evaluate stakeholder willingness and perspectives provided important insights. Despite the survey's relatively limited sample size, we envision engaging more stakeholders to improve the results and add new queries that have emerged after evaluating the responses. Although there were no significant differences in responses depending on upstream vs. downstream residents, more respondents in upper basins would be needed to determine the results with greater certainty. Additional in-depth surveys or in-person interviews may be conducted afterward; to examine how answers change, it would be worthwhile to extend the study further west, toward the upper basin. This research explains how policy implementation constraints might be addressed by incorporating stakeholder preferences and perceptions.

7.3 Estuarine Ecological Flow Considerations

It is abundantly clear that lower Coastal Plain rivers both influence and *are influenced by* downstream estuaries. This strongly suggests that ecological flows for estuaries need consideration. Historically, ecological flow guidance has been limited for estuaries, in part due to limited data and understanding of the freshwater requirements for these ecosystems. However, as mentioned earlier, numerous recent studies and reviews have begun to fill the gap and provide useful information for developing ecological flow guidance, management approaches and policy for estuarine systems, based on research in Europe (Penas et al. 2013), Australia (Chilton et al. 2021), South Africa (Van Niekirk et al. 2019), and the U.S. (Montagna 2021). In the U.S., efforts have been documented for Florida (Palmer et al. 2015), Texas (Montagna 2021), and California (Grantham et al. 2020). Recent reviews by Adams (2014), Chilton et al. (2021) and Stein et al.

(2021) provide detailed reviews of a variety of estuarine studies and include a range of management recommendations.

Adams et al. (2014) reviewed a variety of methods for determining the environmental water requirements of estuaries with examples from systems in FL, GA, CA, and TX. These methods are characterized as inflow-based methods, condition-based methods, and resource-based methods. Inflow-based methods are reliant on hydrological analyses and are based on the assumption that if appropriate freshwater discharge is sustained, then the estuary will be protected. However, it is noted that this simple approach may not account for non-linear responses. Resource-based methods focus on estuarine organisms that are considered to be economically significant. Freshwater discharge recommendations can be targeted to sustain the selected organisms that are deemed to be important in the specific estuary. These approaches may be supported by stakeholders due to the societal and economic importance of the fishery, however this type of approach can require large datasets, and may ignore other important organisms that may have differing flow requirements. Condition-based methods focus on maintaining a specific range of habitat conditions to support ecological integrity. This approach would aim to maintain salinity ranges at specific locations, based on an understanding of the salinity relationship with ecological processes. It appears to be the most closely related method to ecological flows. Although it may be assumed that if ecological flow requirements for inland rivers are met, that may translate to the estuarine water bodies. However, Adams (2014) indicated that this may not always be the case. For example, a study on the Kaaimans Estuary in South Africa showed that the recommended ecological water requirements set for its riverine inputs, were not adequate to maintain the ecological integrity of the estuary (DWAF 2008). Overall, Adams (2014) concluded that the lack of legislation and insufficient institutional support and governance is a barrier to the characterization and application of environmental water requirements for estuaries. This review showed that, although methods are available, implementation can be slow and requires strong governance structures, stakeholder participation, monitoring and feedback (adaptive management).

Van Niekirk et al. (2019) provided a detailed methodology utilized for micro-tidal estuaries in South Africa. Their 7-step approach included: 1. Hydrological assessment; 2. Zoning of the estuary; 3. Identifying the physical states; 4. Characterizing the annual/seasonal distribution of physical states; 5. Predicting biotic responses; 6. Evaluating present and desired conditions; and 7. Developing and allocating environmental flow requirements. They emphasized the need for long-term monitoring to pair with modeling efforts, to improve understanding of the system over time, as well as to evaluate if environmental flows achieve desired objectives.

For the entire Albemarle-Pamlico Estuarine system, in light of the basin's growing water demands there is a need to determine the freshwater flow requirements for the estuary, to ensure that the system can meet its designated uses and that flows are adequate to sustain the ecosystem processes. This contrasts with high flows from storms that further impact salinity regimes, ecological integrity and humans and their infrastructure. Add climate change and sea-level rise, and the interrelated factors affecting flows become starkly important. The studies described above suggest that it would be beneficial to develop a large-scale, holistic framework that could be implemented for the Albemarle-Pamlico Estuarine System. Initial efforts would require identifying and characterizing the physical, chemical, and biological conditions that support critical ecosystem processes in the system (e.g., salinity, nutrient delivery, habitat availability, species migration, light availability, etc.). Numerous agencies within NC DEQ, university laboratories, NGOs, and other organizations have amassed considerable information about the system. For example, APNEP has been developing a program to monitor seagrasses and relate the health of their communities to environmental conditions, especially light availability. The various efforts would serve as an important source for synthesizing an ecological flows approach. In addition, ecological flow efforts for the Albemarle Pamlico drainage basin can have substantial overlap with ongoing efforts through the NC Coastal Habitat Protection Plan (CHPP). Particular issues of CHPP that would be germane are oyster habitat restoration; characterization and protection of distribution, range, and abundance of coastal habitats; management of fisheries species that use these habitats for nursery, forage, spawning, and refuge (NC DEQ 2021: https://deq.nc.gov/media/26810/open).

The relationship between flow and ecological conditions may be discerned via monitoring, modeling, and expert opinion. Improved understanding of the flow-water quality relationships can assist with development of water quality criteria that can provide the basis for evaluating if the system is meeting its designated uses. Linked watershed-estuarine models (e.g., Chesapeake Bay Model; Shenk and Linker, 2013, Hood et al. 2021) can be useful for evaluating the biological response to changing flow regimes. Monitoring efforts are also needed to quantify long-term changes and validate models. Current efforts by the US Geological Survey that could be beneficial for application in the Albemarle-Pamlico Estuarine System include the collaborative efforts with the Chesapeake Bay Program to quantify freshwater flows to the Chesapeake Bay (USGS, 2019). Through these efforts the USGS quantifies the monthly and annual freshwater flows into the Chesapeake Bay to improve understanding of the effects of freshwater inputs on ecosystem conditions. In addition, at select coastal stations along the Atlantic and Gulf coasts, US Geological Survey has developed a Coastal Salinity Index (Rouen et al. 2019). However, currently in the Albemarle-Pamlico estuarine system, stations are limited to the Roanoke River and more stations are needed. This tool characterizes coastal salinity regimes at gages with long-term records and can be utilized to identify salinity extremes. Although excellent long-term physicochemical or biological data are available for the Neuse and Pamlico River estuaries, these data are limited in other portions of the Albemarle-Pamlico estuarine system. It has been suggested that salinity data can be used as an indicator for the relationship between freshwater inflow and the functioning of estuaries, due to the large influence of salinity on multiple ecosystem processes (Peñas et al., 2013). This could be explored with historical data to derive predictions of required flow regimes.

Since water quality variability can be greatest in the riverine-estuarine transition zone, more detailed flow and water quality monitoring is called for in these zones along the major rivers and tributaries within the Albemarle-Pamlico drainage basin. Recent advances in low-cost water level and specific conductivity sensors can provide opportunities to improve understanding of the flow-water quality interactions along this dynamic interface between the river and estuary.

Within the Albemarle-Pamlico estuarine system there are opportunities to compare estuarine function across a gradient of freshwater input/salinity gradient to see how systems shift with increased salinity e.g., fresher Albemarle Sound vs. saltier Pamlico Sound utilizing a time for space approach to evaluate what happens when systems get saltier. In the riverine-estuarine transition zones it may be possible to identify systems that have greater extent, intensity, and duration of inland saltwater intrusion events and compare ecological communities from fresher to saltier conditions.

As understanding of the dynamic nature of the riverine-estuarine transition zone and freshwater requirements of coastal rivers and estuaries is advanced, it is important to educate stakeholders and resource managers on the importance of freshwater flows to the estuary. Current NC policy and regulations do not adequately consider the potential effects of withdrawals on the tidal rivers and estuaries downstream.

7.4 Moving to Policy and Management of Ecological Flows

The full value of this work will not be realized until the scientific information and ideas are translated into policy and ultimately management of river flows. This translation will likely be a challenge. Recommendations of the authoritative report by the EFSAB (2013) have been deferred largely because of strong political forces resisting perceived restrictions of water use. If APNEP finds this report and efforts by the Ecological Flows Action Team useful, it will need to muster support of the Partnership and beyond. Here we recommend actions to do so.

We propose that APNEP hold an ecological flows summit. This might be part of its next conference or a stand-alone event. The purpose would be to organize stakeholders to develop support and strategies to advance system-wide policies related to ecological flows. The meeting could highlight several major points: what we know, inclusion of estuaries and watershed approach, recognition of the interconnection of human and natural systems, inclusion of high as well as low flows and thus storms, and links to both resiliency and climate change. Presentations would be followed by substantial feedback and discussion on next steps both in science and bringing science to policy. The Ecological Flows Action Team can work with staff to identify appropriate attendees, speakers, and facilitators.

7.5 What we know

There is now enough scientific information to advance guidelines for adopting an ecological flows approach within the APES region. The 2013 EFSAB report is a benchmark for flows where flows are unidirectional and the major determinant of depth. The report was developed for planning purposes. Thus, it lacks specificity for any regulatory criteria but provides guidance specific to North Carolina that could be used in future efforts. APNEP has furthered understanding through supporting the present work and that of O'Driscoll et al. (2018). These concentrate on the Coastal Plain and, combined, represent enough information to initiate policy recommendations. From a management perspective, there is a need to resolve the stalemate on the inclusion of ecological flows in the hydrological models used by DWR for planning purposes. The current hydrological model of choice, OASIS, does not function in tidal rivers. There is a need to identify and implement hydrological models suitable for use in tidal rivers that are capable of integration with the OASIS model. Statutorily, DWR is required to develop models for all 17 river basins, including those coastal basins where OASIS does not function, G.S. 143-355(o).

It is also important to consider that the current instream flow program doesn't look at cumulative impacts, new municipal supplies or expansions require withdrawals to be < 20% of 7Q10, however this would be on a case-by-case basis. For low flows there is a concern that the cumulative impacts of withdrawals can have greater ecological impacts.

7.6 Inclusion of Estuaries and Watershed Approach

Waterways within the Lower Coastal Plain require a watershed perspective. Upstream flows in rivers impact the water quality (especially salinity structure) and ecological status of their reaches within the Lower Coastal Plain and downstream estuaries. It is now abundantly clear that downstream processes are, also, important to flow, water quality and ecological status of rivers in the Lower Coastal Plain. Field work, modeling and agency delineations too often fail to properly recognize and accommodate a holistic, system-level approach. This perspective is recognized not only in our work but in a growing body of scientific literature and regulations in other regions. The summit can help begin to educate attendees on what is now understood.

7.7 Recognition of the Interconnection of Human and Natural Systems

There is a tendency to separate human and natural systems and, thus, perpetuate competition between them. A zero-sum game is proffered that regulations that help nature hinder humans and vice versa. But this is not necessarily true if one takes a large-scale view of socio-ecological systems. The term "ecological flows" has connotations to some that humans are limiting themselves to the benefit of nature. This view fails to recognize ecosystem services that benefit humans. Effort will be needed at the summit and elsewhere to better educate stakeholders about a more holistic, human-inclusive view. Given the political baggage of the term, APNEP may even wish to use another term. Others have used "environmental flows" and "instream flows," which may be more palatable to certain stakeholders.

7.8 Inclusion of High as Well as Low Flows

A holistic view of ecological flows could include consequences of both low and high flows. Both have impacts on natural ecosystems surrounding the waterways and on humans, their infrastructure, and their activities. Only low flows are generally addressed in ecological flows because the purpose is to plan or regulate water use by humans. But flows fluctuate widely over a range of time scales and, in doing so, create a spectrum of impacts. Periods between extremes of either low flows from droughts or high flows from storms occur at intervals of years or even decades. Often humans respond to the most recent and perhaps most severe events. Human perception of nature, also, focuses on the near-term condition. There can be loss of perspective of impacts from an opposite extreme. The summit should include a session addressing the consequences and potential benefits and detriments to planning that addresses this spectrum.

7.9 Links to Both Resiliency and Climate Change

The holistic view places planning into the model of building resiliency. Currently resiliency discussions often focus on resilience to climate change. In the Coastal Plain, climate change impacts are seen to come from elevated temperatures, sea-level rise, and increased frequency and severity of storms. But they, also, include increased frequency and severity of drought. All of these are within the context of increased human populations in many areas and consumption of natural goods and services. Adopting protocols for ecological flows, therefore, becomes part of building resiliency.

It is hoped that a well-organized and attended summit will help educate stakeholders on these topics. The stakeholders must represent a wide variety of interests and disciplines. APNEP is structured well to both conduct the summit and make it inclusive. The results should be suitable for future comprehensive planning.

Strategies should be proposed for incorporating ecological flows into policy and environmental management. One possible strategy might be to initiate an equivalent to the Coastal Habitat Protection Plan but for comprehensive ecological flows. This may overlap with several key points from APNEP's Comprehensive Conservation and Management Plan (2012) including recommendations to: "Facilitate the development and implementation of an integrated freshwater habitat protection strategy" (Action B2.1) and: "Facilitate the development and implementation of basinwide water management plans to ensure that no less than minimum in-stream flows are maintained" (Action D3.2). The major point we make here is that the accumulation of information on ecological flows is such that next steps should include translating science to policy.

Broader discussion is also needed to consider potential improvements to NC water use policy and revisiting the recommendations from the 2008 Report of the Water Allocation Study of the NC Environmental Review Commission (Whisnant and Holman, 2008). These earlier efforts discussed the potential threats to freshwater ecosystems due to the lack of effective water use policy in NC. The concerns voiced are still highly relevant, perhaps more so with population growth, growing water demands and increased hydrological variability associated with climate change. As the population grows, water use increases, and land use and climate change lead to more hydrological variability there is a growing need to develop adequate policy to manage water withdrawals, particularly during low flow periods.

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Appendices

Appendix A- Existing Data for Evaluating Coastal Plain Ecological Flows in the Albemarle-Pamlico Estuary Region

O'Driscoll et al. 2018- Report to APNEP

Executive Summary

This study focused on the status of available flow and ecological flow-related data for the Albemarle-Pamlico drainage basin. During our data search and compilation there were numerous notable data gaps. The main data gaps were associated with streamflow, groundwater, evapotranspiration, salinity, water use, and ecological response data. Gaps in water use data may influence the accuracy of water budgets for watersheds in the region. In general, there is a lack of publicly-available, fine-scale water withdrawal data sets that can be used to assess the temporal variations in water usage. This decreases the capability to evaluate how anthropogenic changes such as groundwater pumping and surface water withdrawals might impact low flow in streams, particularly during high demand summer months. Based on the surface water, groundwater, meteorological, and water use data available we recommend a pilot study to determine if accurate water budgets can be constructed with pre-existing data at the watershed-scale. A water budget for a pilot watershed would be constructed with publicly available data, while at the same time the watershed would be intensively monitored to gain a better understanding of how accurate the water budget using publicly available data predicted the flux of water. It is hypothesized that improvements in Coastal Plain water budgets could be made if georeferenced data could be collected monthly and verified with water meters throughout the pilot study watershed. Since the Central Coastal Plain Capacity Use Area (CCPCUA) falls within the Albemarle-Pamlico Basin, a study watershed within the CCPCUA would be ideal. Water use is tracked more closely in the CCPCUA and since 2002, the data has been available to the public. Based on long-term flow records, Contentnea Creek, may be a good candidate for further study. In addition, the Little River shows evidence of declining low flows and further study could help to explain why. The Trent River station near Trenton is one of the limited number of discharge stations adjacent to the Outer Coastal Plain that has a long-term record, this watershed would also be a good candidate for coastal ecological flow research.

These and other potential studies could focus on answering several research questions:
- What are the most accurate and least accurate water flux and use estimates and how can gaps in water use data be filled?
- What are the relative influences of meteorological forcing vs water withdrawals on low flows?

- Are current low flows protective of ecological integrity? What threshold of water use would adversely affect streamflow and/or ecological integrity?
- How will climate change, withdrawals, and land-use change affect low flows in the future?
- What are the general stressor-response relationships between flow alteration and ecological health?
- Based on pre-existing data, can the stressor-response relationships be adequately evaluated and if not, what types of data are needed in the future?
- What are barriers to understanding the dominant influences on ecological flows at the watershed-scale?

Although there is a database of ecological flow work in the southeast, few of these studies were conducted in the Albemarle-Pamlico drainage basin. We recommend seeking funding and partnerships to include watershed-based ecological flows research focused on the ecological responses to low flows and variability in pulses, flooding, and salinity. The earlier work by NC DEQ (2013) also concluded that more information is needed on the biological response to streamflow reductions, particularly for headwaters and coastal plain streams, but also for large rivers. Since climate change and land-use change may affect future river flows in the region, work focused on potential changes to flows, salinity, and ecological responses associated with future climate and land-use change would also be needed to help guide water resources, fisheries, and land-use management in the basin.

A first step towards understanding ecological flows in the region would be to perform ecological flow analysis on the long-term discharge records along unregulated river reaches in the Albemarle-Pamlico drainage basin. We recommend that these analyses be performed on the discharge records at the USGS stations with long-term data (>30 years). We recommend that the flow analyses first be performed using the Indicators of Hydrologic Alteration software and on streams categorized based on the initial classification system (Coastal Plain tidal, Coastal Plain low-slope, Coastal Plain medium-slope, and Piedmont) suggested by the Coastal Ecological Flow Working Group (CEFWG) (NC DEQ 2013). If the USGS flow stations correspond with sites where NC DEQ has collected biological data, flow metrics can be compared with diversity indices for fish or macroinvertebrates.

Based on the number of agencies collecting water use and wastewater discharge data, it would be worthwhile to bring together water use and water flux experts from USGS, NC DEQ, NC Dept. of Agriculture and Consumer Services, NC Climate Office, NC Dept. of Health and Human Services, water utilities, and other stakeholders with the goal of developing a comprehensive water accounting system for the region. An interagency plan is needed to address the challenges, costs, and other issues associated with coordinating a more comprehensive water use and wastewater return-flow database for the Albemarle-Pamlico Drainage Basin.

Based on ecological flow development work in other states, numerous states in the southeast have data and experience developing ecological flow criteria. Many suggest that adaptive management with stakeholder involvement is an important component of ecological flow management. This kind of approach in which federal, state, and local agencies work in cooperation with stakeholders to achieve ecological flow management objectives may be the most likely to succeed. In most states, the water or environmental agency in the state takes the lead, in this case that would be the NC DEQ. Moving forward, APNEP and DEQ could collaboratively develop a process to define ecological flow goals and criteria for the drainage basin. Based on Session Law 2010-143, DEQ is required to develop basinwide hydrological models for each of NC's 17 river basins to predict the places, times, and frequencies at which ecological flows may be adversely affected in North Carolina (NC DEQ 2013). Future work on ecological flows in the Albemarle-Pamlico drainage basin should aim to complement the mandated efforts by NC DEQ.

Appendix B- Water Use and Wastewater Return Flows in the Trent

Water infrastructure (e.g., groundwater wells, surface water intakes, water and wastewater treatment facilities, and dams) are vital to serve communities, but they have potential to alter natural hydrogeological processes. Numerous studies in the past (n= 152) found that modifying natural flow regimes resulted in negative ecological changes. The most commonly reported flow alterations included dams and impoundments (n= 88), water diversions (n= 17), groundwater abstraction (n= 6), and levees (n= 7) (Poff and Zimmerman, 2009). Thus, dams, groundwater wells, and surface water intakes can reduce the volume of water in downstream reaches of the Neuse River, especially during drought conditions. Wastewater discharges from water and/or wastewater treatment plants can recharge streams, but may degrade water quality within the streams, especially during low flows when dilution and dispersion is limited. Both the Neuse River Basin and the Trent Watershed have critical water infrastructure features that have altered natural flow regimes and have potential to affect ecological flows. Many of these features are within the Piedmont region of the Neuse River Basin (Figs. 38-40). Approximately 73%, 89%, and 80% of potable water supplies, National Pollution Discharge Elimination System (NPDES) permits, and dams, respectively, were located within the Piedmont (Table 13). This result was expected considering the Piedmont contains larger, more populated urban areas, including portions of Raleigh, Durham, and Wake Forest. Thus, the demand for potable water and centralized wastewater treatment is greater than the Coastal Plain portions of the Neuse River Basin. The number of groundwater wells far exceeded the number of surface water intakes (Fig. 38; Table 13). In 2008, NC DEQ (2010) estimated that approximately 78% of residents (934,165 out of 1,202,129) served by local water supply systems received potable water from surface water sources. Thus, the remaining 22% of residents (267,964) received potable water from groundwater sources. Additionally, NC DEQ (2010) estimated that in 2020, surface water would provide potable water for 1,235,224 people in the Neuse River Basin (~79% of all residents). Thus, groundwater would supply 334,137 people with potable water. We reassessed this percentage of residents using publicly available data on public water supply water sources (NC OneMap, 2023). We found that surface water supplied 1,219,146 people with potable water within the Basin and that accounted for approximately 73% of the total population. Therefore, groundwater supplied the remaining 27% of the population, or 462,371 residents, with potable water. Future work should focus on estimating the mean daily, monthly, and annual usage of surface water and groundwater supplies throughout the Neuse River Basin. These data could help to better understand drivers behind ecological flows, especially during drought conditions.

There also appeared to be a trend between urban development and permitted design flow rate (Fig. 39). Of the 696 permitted NPDES facilities, 24 of them had a design flow that exceeded 0.75 MGD. Most of these facilities (n= 18) are wastewater treatment plants that serve urban areas within the Neuse River Basin (e.g., Raleigh, Durham, Goldsboro, Wilson, Cary, Kinston, New Bern, Apex, Farmville, US MCAS Cherry Point, Havelock, Fuquay-Varina, Hillsborough, Clayton, and Benson). Three of these facilities are wastewater treatment plants that serve districts of smaller municipalities (e.g., Johnston County Public Utilities, South Granville Water & Sewer Authority, Contentnea Metropolitan Sewerage District). The remaining 3 permitted facilities are for industrial process and commercial wastewater discharges (e.g., Weyerhaeuser in New Bern, NC and 2 permits for Covation Biomaterials in Kinston, NC). There were 3 NPDES facilities that are permitted to discharge ≥20 million gallons of wastewater daily, including the wastewater treatment plant for the City of Raleigh (75 MGD), Weyerhaeuser in New Bern, NC (32 MGD), and a wastewater treatment plant for the City of Durham (20 MGD). In addition to these NPDES facilities, there are numerous permitted water and wastewater treatment plants within and adjacent to Raleigh, Durham, and Hillsborough with design flow rates < 0.75 MGD. One limitation with this geodatabase is that 235 facilities have a reported design flow rate of 0 GPD. Furthermore, there are 254 permits that are currently listed as expired, which could be due to a facility that has permanently closed, or their permit reapplication may currently be under review. Some of these limitations could be overcome by updating the geodatabase using NC DEQ's Laserfiche documentation system to correct for missing design flow rates and update permit status. Future work should consider this approach to further understanding of where actively discharging facilities are within the basin.

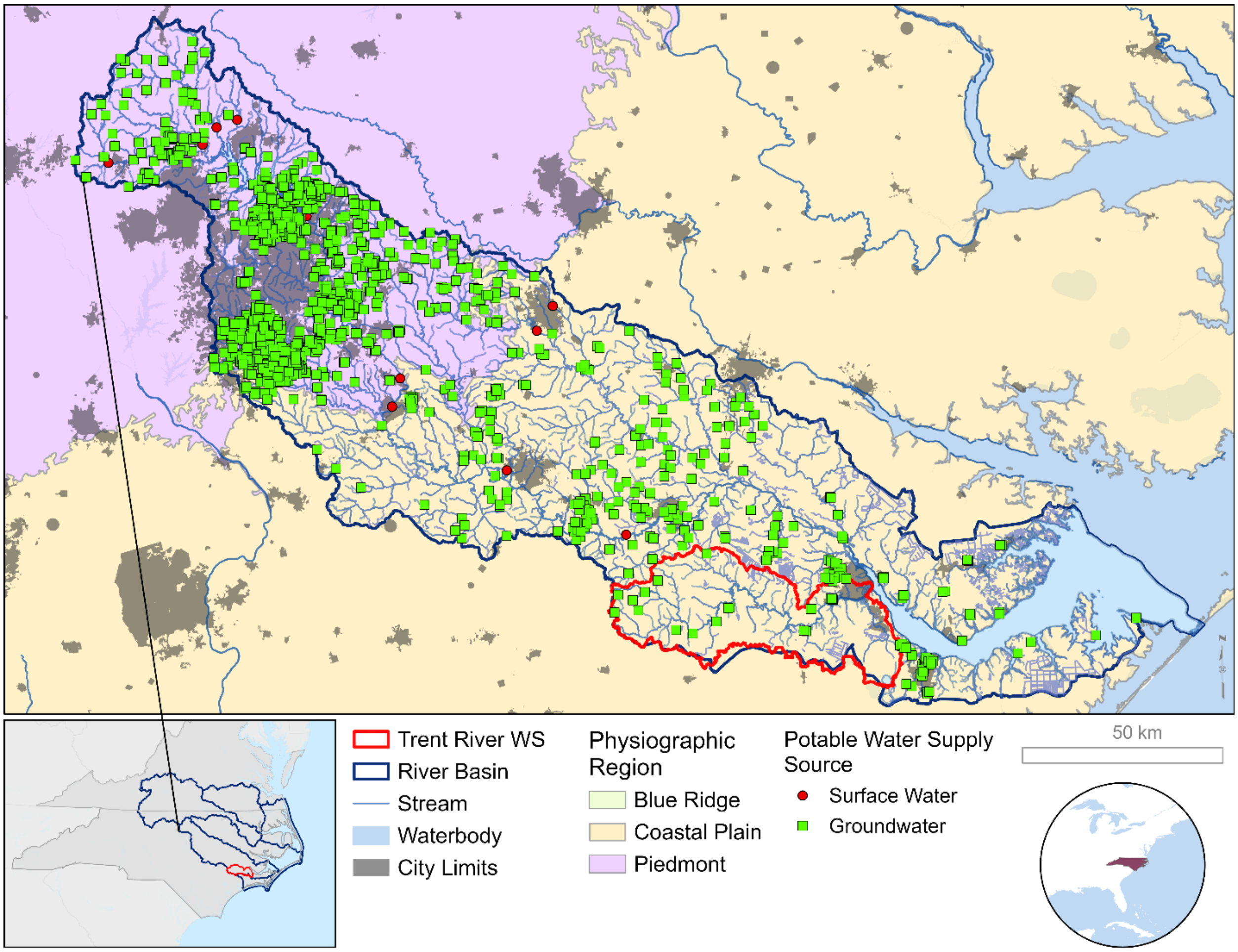

Figure 38. Map of the Neuse River Basin depicting the locations of potable water supplies and physiographic region. Red circles denote surface water intakes, whereas green squares denote groundwater wells. WS= watershed.

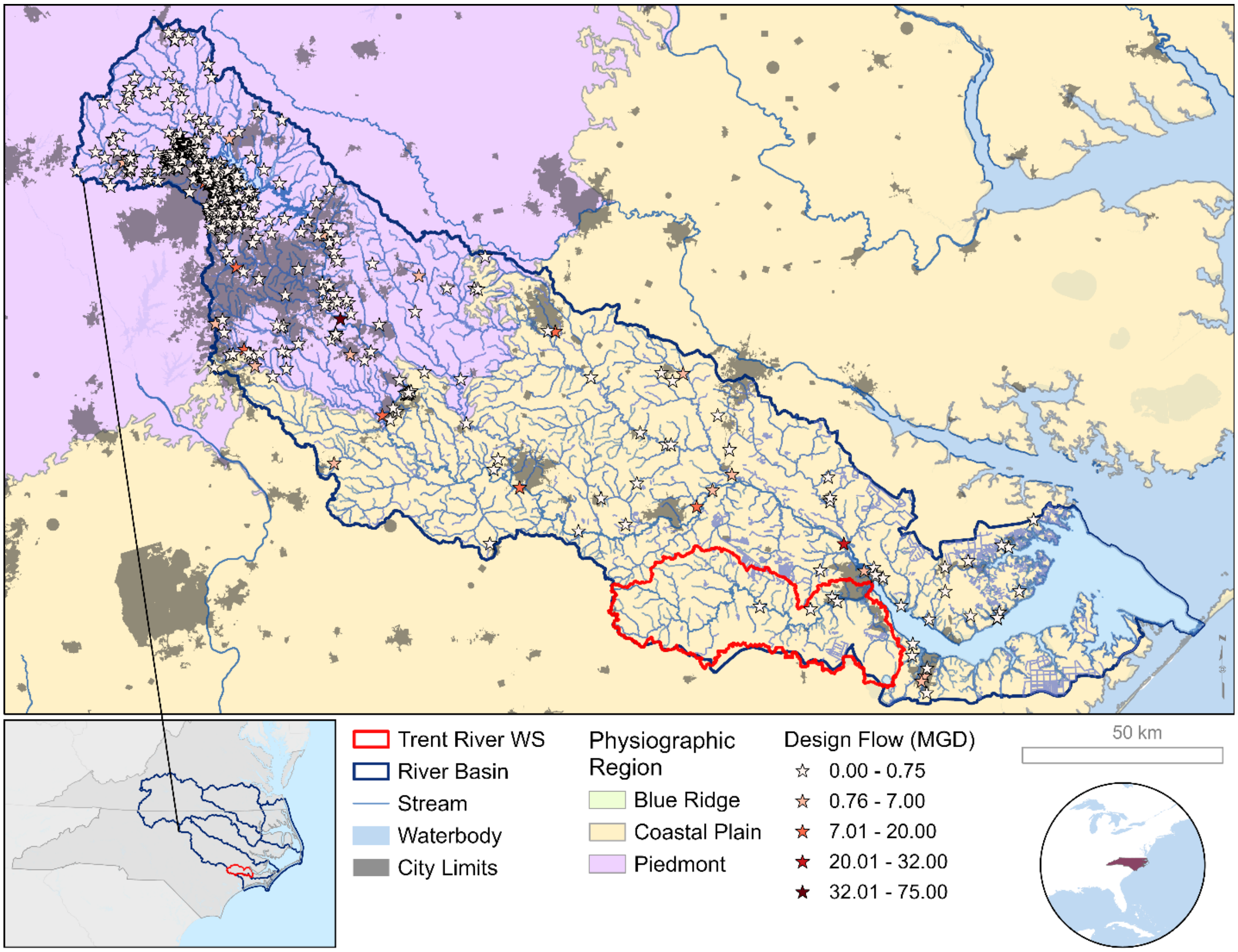

Figure 39. Map of the Neuse River Basin depicting the location of permitted water and wastewater treatment facilities and physiographic region. Stars denote the approximate location of the outfall pipe and the shading corresponds to the permitted flow with darker shades denoting higher allowances. Design flow denotes the maximum daily discharge allowance expressed in millions of gallons per day (MGD). WS= watershed.

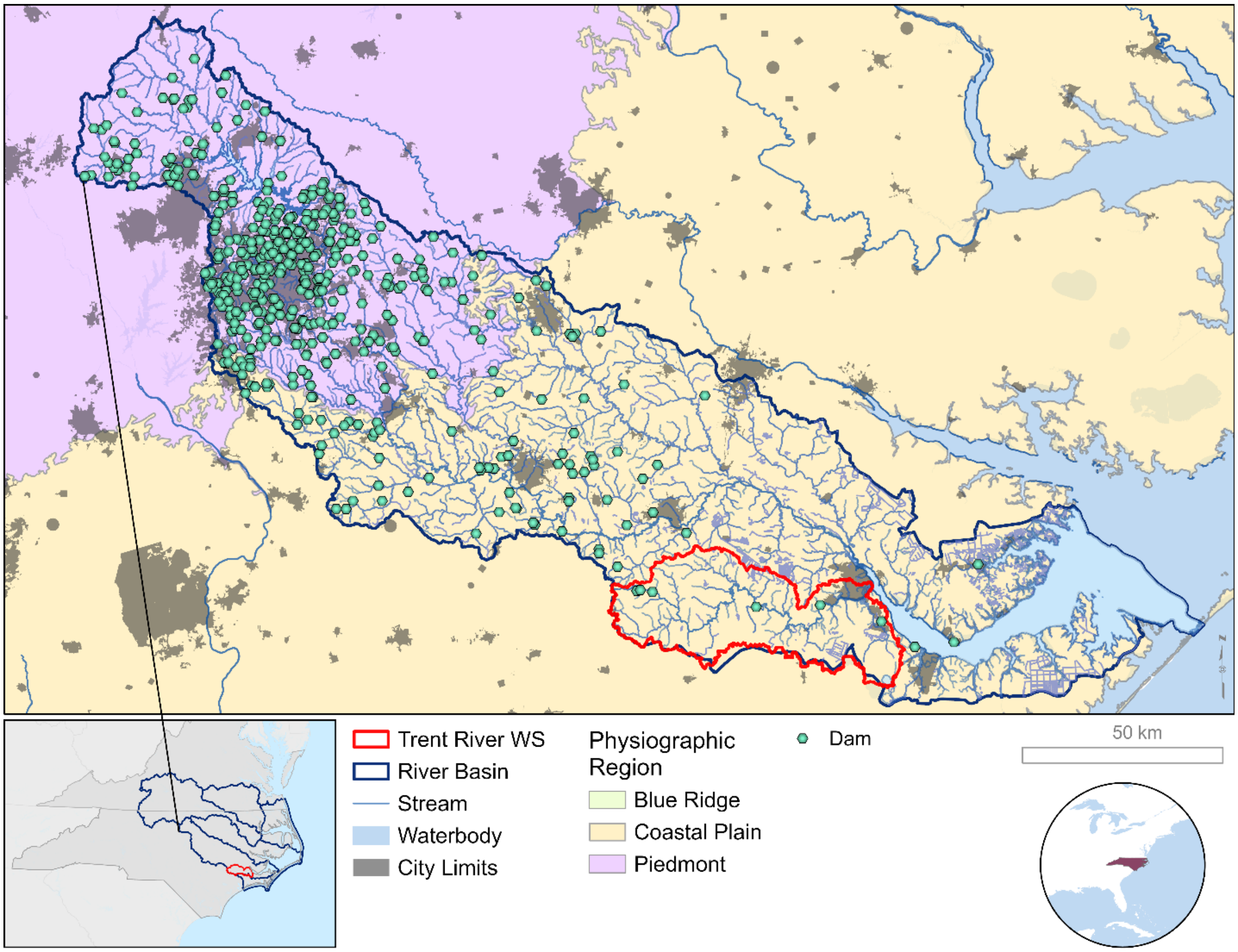

Figure 40. Map of the Neuse River Basin depicting the location of dams and physiographic region. Teal hexagons denote the approximate location of dams. WS= watershed.

Table 13. Hydrogeologic features in the Neuse River Basin grouped by physiographic region. The headwaters of the Neuse River do not extend into the Blue Ridge Mountains, thus this region was omitted. NPDES= National Pollution Discharge Elimination System.

Feature Class	**Physiographic Region**		
	Piedmont	**Coastal Plain**	**Total**
Potable Water Supply	1045	390	1435
Groundwater	1035	386	1421
Surface Water	10	4	14
NPDES Permit	620	76	696
Dam	395	99	494

Impoundments, groundwater withdrawal, and discharge from water and wastewater treatment facilities could influence ecological flows within the Trent River Watershed (Fig. 41). Currently, there are 6 impoundments within the watershed. Most of the impoundments (4 of 6) are located adjacent to or upstream of Trenton, NC. One dam is located immediately upstream of River Bend. The furthest downstream dam is on the headwaters of Lee Branch, which eventually drains to Brice Creek, a tributary to Trent River. Most of the impoundments are listed for irrigation or recreational purposes. The max storage for these dams ranged from 18 – 432 acre-ft. The largest impoundments are within Trenton, NC and approximately 10 km downstream of the origin of the Trent River. At the time of the current study, there were 21 groundwater wells within the Trent River Watershed (Table 14). Most of the groundwater wells are screened to depths ranging from 105 – 576 ft, with the deeper wells tending to be in higher elevations of the watershed ($\rho = 0.70$; $p < 0.01$) (Table 14). The source of groundwater for these wells includes the Surficial, Black Creek, Peedee, Upper Cape Fear, and Castle Hayne Aquifers (NC DEQ, 2023b). Well yields ranged from approximately 10 – 700 gallons per minute (GPM) or 0.014 to 1.008 million gallons per day (MGD). The well with the lowest yield is a non-community, transient well that does not contain any water use data, likely due to its transient usage. In 2021, wells within the New Bern and Jones County Public Water Supply tended to have the highest mean daily use. Additionally, maximum daily use was typically about twice the mean daily use (Fig. 42). There were 3 wells not included in Figure 42 because the Local Water Supply Plan did not include any data for the non-community, transient well within River Bend and Wells 9 and 10 within the Jones County Regional Water System. Most of the water supply wells are upstream of Trenton, NC. There are only 7 wells located downstream of Pollocksville, which includes Wells 9 and 10 in the Jones County Regional Water System, Wells 1-3 in River Bend's system, and Well 12 in New Bern's system (Fig. 41). In 2021, mean daily water use from wells within and upstream of Pollocksville totaled to be 1.55 MGD, whereas the River Bend and New Bern wells totaled 0.61 MGD. These data suggest that impoundments and groundwater abstraction may have a larger influence on natural hydrology in upstream reaches of the Trent River. To put in context with baseflow along the Trent, the 7Q10 is 1 cfs and 7Q2 is 4.3 cfs, which would equate to 0.65 MGD and 6.6 MGD, respectively. If consumptive withdrawals are greater than ~0.2 cfs or 0.3 MGD during extreme low flows (1cfs), there may be noticeable impacts. However, a more detailed water budget and information on river-groundwater interactions is needed.

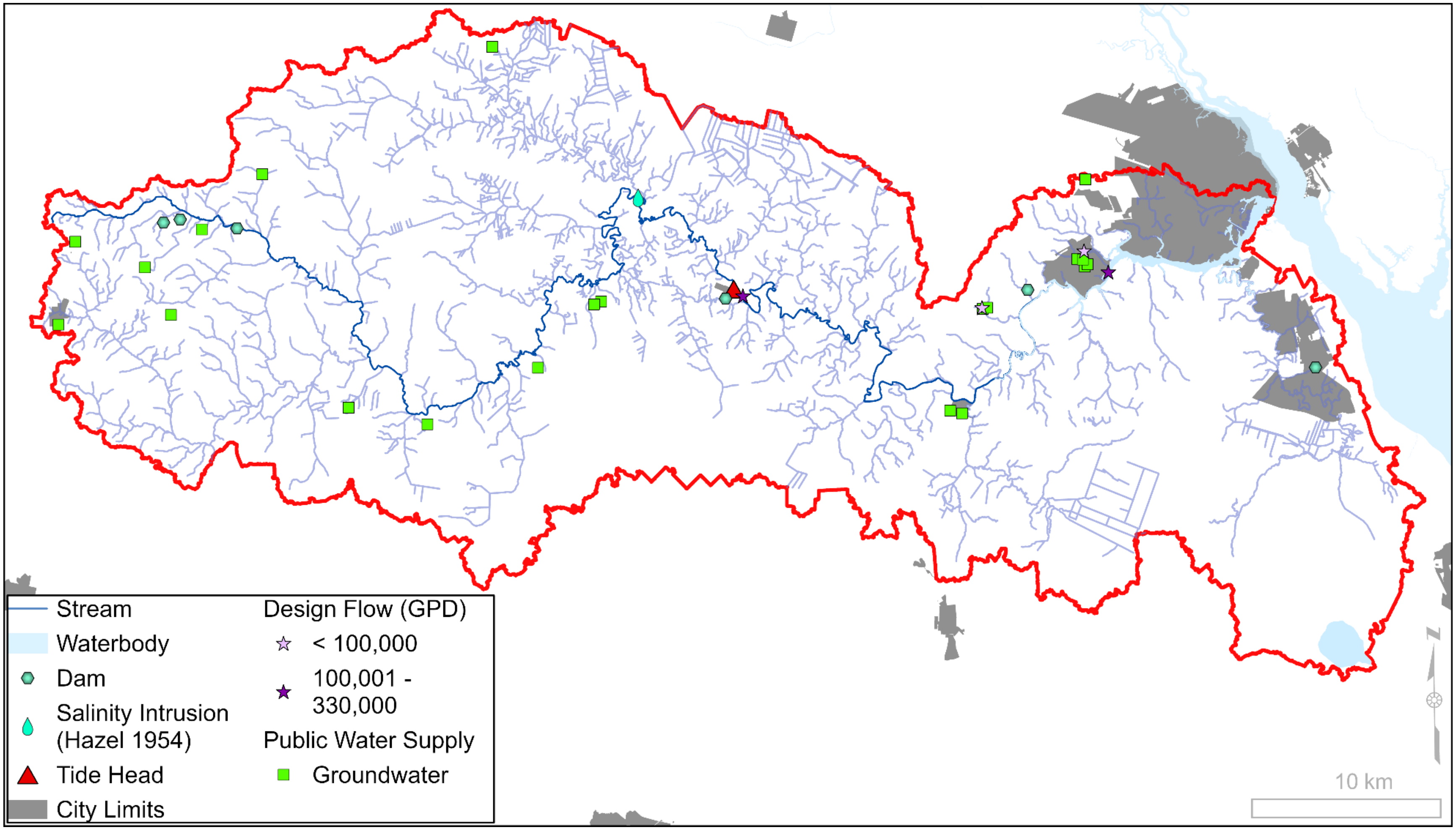

Figure 41. Map of the Trent River Watershed and major hydrographic features. There are 21 public water supplies all sourced from groundwater (green squares), 2 wastewater treatment plants and 2 water treatment plant (purple-shaded stars), and 6 dams (teal hexagons). The red triangle located near Pollocksville, NC is the tide head and the cyan water drop symbol denotes the extent of salinity intrusion from Hurricane Hazel in 1954.

Table 14. Summary of well yield, elevation, and depth of groundwater wells used by the 6 public water suppliers in the Trent River Watershed. GPM= gallons per minute; MGD= million gallons per day; NCT= non-community, transient well.

Well #	Location/Well Field	Well Yield (GPM)	Well Yield (MGD)	Elevation (ft)	Well Depth (ft)
12	New Bern	700	1.008	32	269
1	River Bend	500	0.72	9	105
2	River Bend	250	0.36	9	110
3	River Bend	350	0.504	17	103
1-NCT	Peck (River Bend)	10	0.0144	8	150
1	Pollocksville	150	0.216	27	182
3B	Pollocksville	175	0.252	23	196
1	Jones County	200	0.288	40	482
2	Jones County	250	0.36	40	498
3	Jones County	325	0.468	66	576
5	Jones County	200	0.288	54	479
7	Jones County	275	0.396	60	303
8B	Jones County	200	0.288	61	317
9	Jones County	360	0.5184	35	260
10	Jones County	355	0.5112	33	254
1	Pink Hill	150	0.216	139	388
8	Deep Run WC	302	0.43488	135	370
9	Deep Run WC	305	0.4392	109	421
10	Deep Run WC	403	0.58032	97	250
11	Deep Run WC	300	0.432	157	336
12	Deep Run WC	400	0.576	126	375

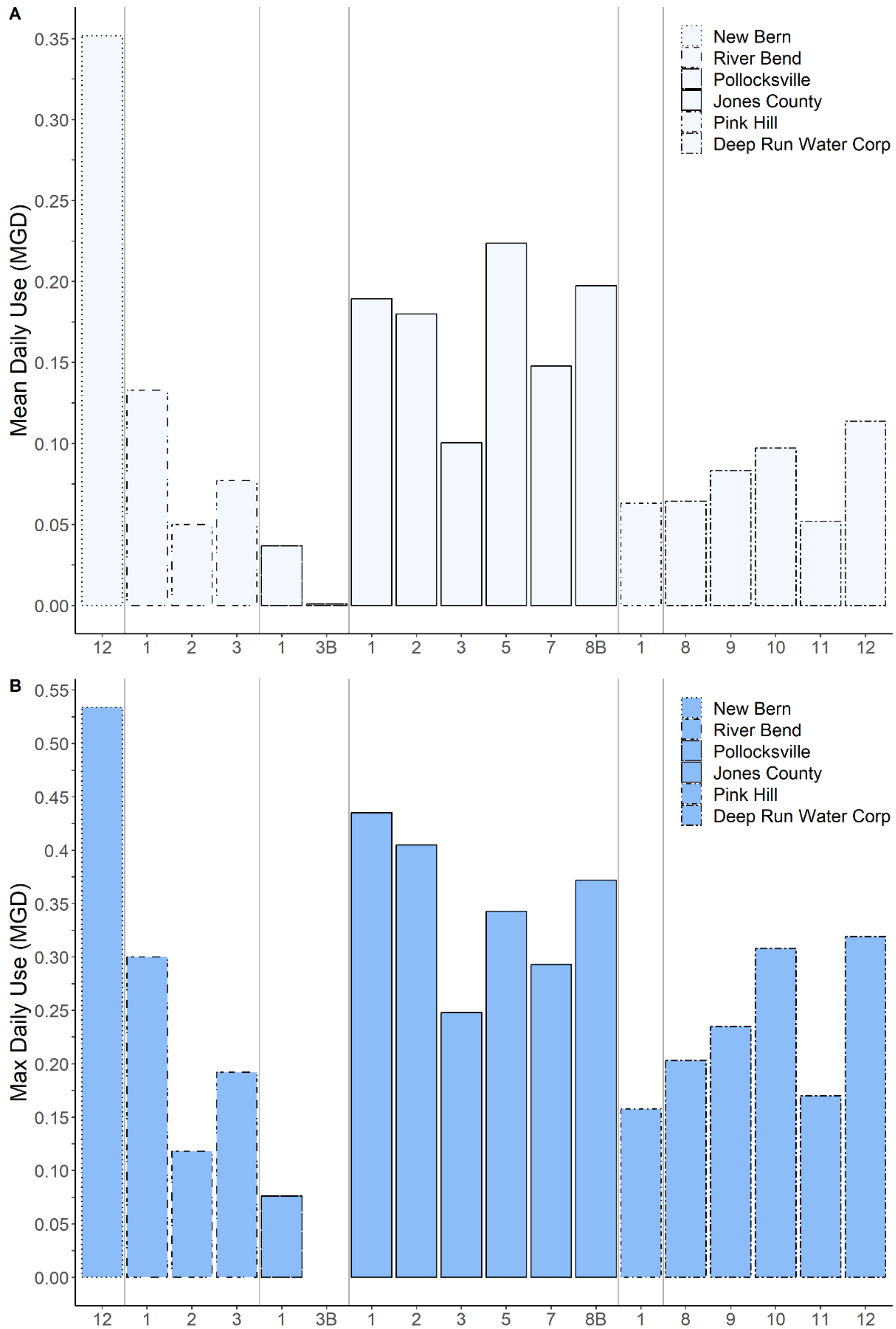

Figure 42. Mean (A) and max (B) daily water use in million gallons per day (MGD) from public water supplies in the Trent River Watershed from 2021. Numbers on the x-axis refer to well identification numbers.

Water use within the Trent River tended to increase during summer months, especially within the City of New Bern (Fig. 43). This trend was subtle within the Town of River Bend and the Town of Pink Hill. The Town of Pollocksville exhibited large variability from January – April due to a substantial increase in mean daily water use in 2014. During this same timeframe, the mean daily water use was reported as 2.20 ± 0.45 MGD. This appeared to be a high outlier that may represent an error since these same water use trends were never repeated. If these data are omitted, the overall mean from January – April reduced to 0.05 ± 0.01 MGD, which was similar to other reported months. Thus, Pollocksville did not exhibit a strong seasonality trend in water use. The differences in seasonal effects were likely influenced by population differences between municipalities. The City of New Bern, Jones County Regional Water System, and Deep Run Water Corporation have approximately 17,000, 4,300, and 5,400, respectively, connections, whereas the other municipalities have < 1,500 connections (Table 15). The seasonal high water use overlaps when baseflow tends to be lowest (Fig. 4). This phenomenon can result in declined water level within stream channels, which may degrade or destabilize aquatic habitat. Abnormally dry or drought conditions can further exacerbate this phenomenon. It is possible that these periods of low flow can extend into late fall if the storm season does not deliver adequate precipitation to offset evapotranspiration and anthropogenic uses resulting in water loss.

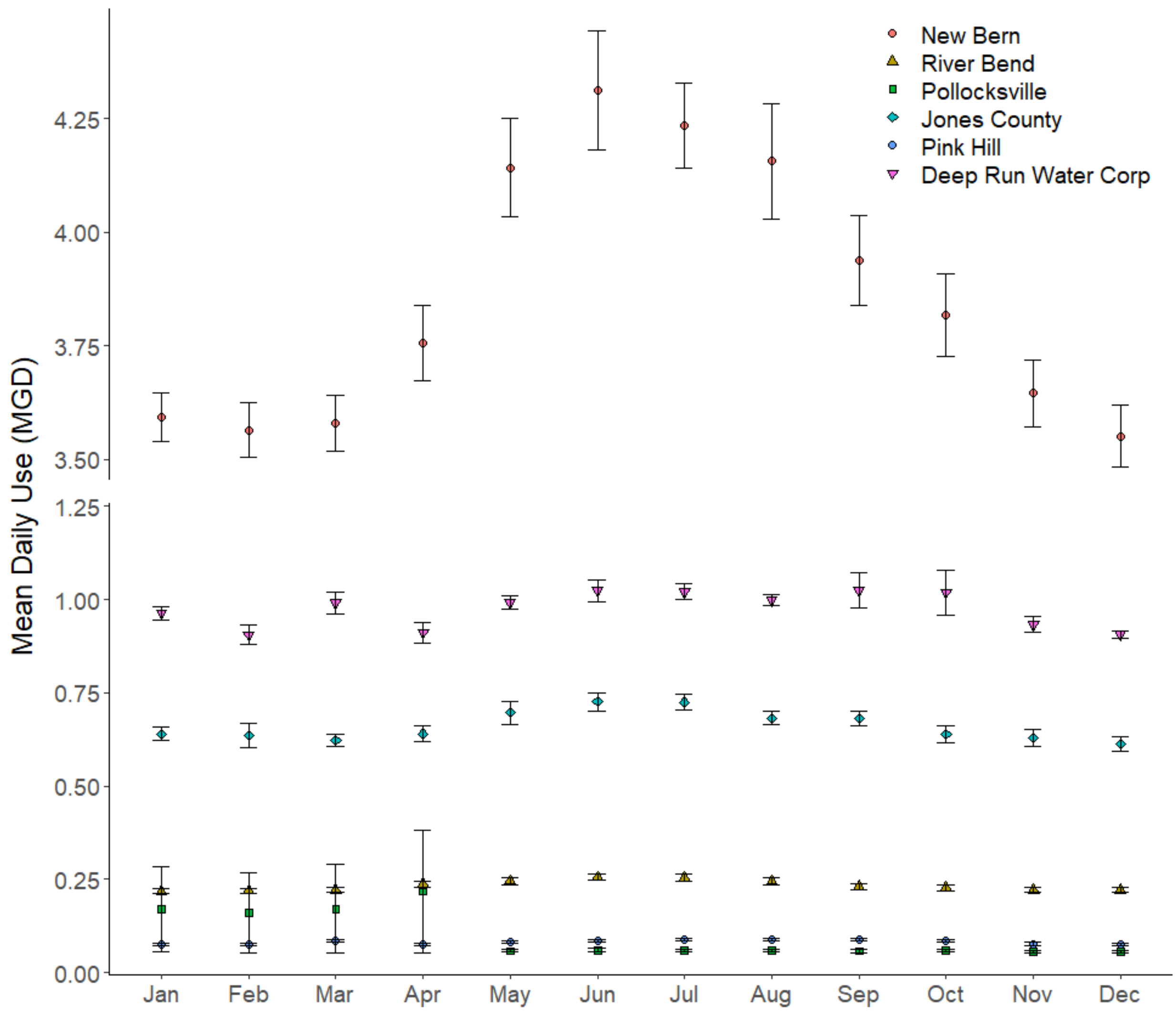

Figure 43. Monthly trends in mean daily water use (million gallons per day [MGD]) for the 6 public water supplies within the Trent River Watershed. Water use data was compiled over an 18-year period (1997, 2002, 2006 – 2021) from NC DEQ (2023a). Error bars are based on the standard error of the mean. The New Bern and Deep Run Water Corporation water suppliers have groundwater wells outside of the Trent River Watershed, thus water use data includes customers outside of the studied watershed.

Table 15. Summary of 2021 water usage statistics from the 6 public water systems within the Trent River Watershed compiled by residential, commercial, industrial, and institutional uses. Number in parentheses denotes the total percentage of each usage type relative to the total. Data were compiled from the NC DEQ Division of Water Resources (2023a). MGD= million gallons of water per day; NB= New Bern; RB= River Bend; PO= Pollocksville; JC= Jones County; PH= Pink Hill; and DR= Deep Run Water Corporation.

Water Usage (2021)	**Public Water System**					
	NB[1]	**RB**	**PO**	**JC**	**PH**	**DR[1]**
Mean Daily Use (MGD)						
Residential	1.996	0.137	0.028	0.385	0.0284	0.631
Commercial	0.855	0.01	0.0078	0.0139	0.0143	0.046
Industrial	0.061	0.008	0	0	0.0002	0
Institutional	0	0	0	0.0448	0.0034	0
Number of Connections						
Residential	16605 (89.9%)	1468 (99.1%)	238 (95.6%)	4106 (93.5%)	268 (74.9%)	5318 (99.4%)
Commercial	1845 (10%)	13 (0.9%)	11 (4.4%)	50 (1.1%)	80 (22.3%)	30 (0.6%)
Industrial	22 (0.1%)	1 (0.1%)	0 (0%)	0 (0%)	3 (0.8%)	0 (0%)
Institutional	0 (0%)	0 (0%)	0 (0%)	236 (5.4%)	7 (2%)	0 (0%)

[1]= Public water system includes wells that are outside of the Trent River Watershed, thus use statistics are over-estimated.

Currently, there are 4 facilities with NPDES "discharge" permits within the Trent River Watershed has 4 (Fig. 44). These facilities include the Town of River Bend's water and wastewater treatment plants, the Jones County water treatment plant, and the Town of Trenton's wastewater treatment plant. There are at least 2 other non-discharge facilities within the watershed, which are wastewater treatment plants that serve the Town of Pollocksville and another that serves the Town of Pink Hill. A NPDES discharge permit allows designated facilities to release effluent from water and/or wastewater treatment plants directly to surface waters. Non-discharge facilities are those that land apply wastewater effluent to sprayfields rather than directly discharge to surface waterbodies. Of the 6 water or wastewater treatment plants within the watershed, wastewater data were only available from the water and wastewater treatment plant in River Bend, the wastewater treatment plant in Pollocksville, and the wastewater treatment plant in Pink Hill. Wastewater generated from water purification or wastewater treatment from New Bern is not discharged to the Trent River Watershed, thus these data were not evaluated.

Mean daily discharge from water and wastewater treatment plants exhibited a seasonal trend within River Bend and Pink Hill, whereas Pollocksville did not (Fig. 44). Monthly mean daily discharge data for River Bend is combined for the water and wastewater treatment plants. It is possible that the wastewater treatment facility may exhibit a similar geometry as Pink Hill if these data could be subdivided at the monthly scale. This trend was similar to seasonal trends in baseflow discharge in streams (Fig. 4) and tended to be opposite as seasonal trends in water use (Fig. 43). Thus, the seasonal trends in baseflow stream discharge, water use, and wastewater discharges suggest that the highest risk of ecological degradation from reduced water volume overlap with summer months. The inverse relationship between wastewater discharges and water use could provide insight into how water is used within communities. During summer months, citizens may use water for irrigation of lawns, flowerbeds, gardens, etc., washing automobiles, recreational water activities (e.g., pools, sprinklers, etc.), or other outdoor water uses. Water consumptive activities occurring outdoors typically do not enter wastewater treatment facilities. Thus, if the increased water use in the summer was predominantly for outdoor activities, then mean daily discharges from wastewater treatment plants would not likely increase in tandem with water use. Additional information on the volume of water used for irrigation activities relying on public water supply across various land uses is needed. The North Carolina Agricultural Water Use Survey did not report any uses from Jones County in 2014, but the most recent report in 2020 reported 13 operations (groundwater withdrawals) with an average withdrawal per county of 228,778 gallons/day (https://webservices.ncleg.gov/ViewDocSiteFile/18240#:~:text=The%20annual%20average%20daily%20water,contacted%20by%20telephone%20follow%2Dup.)

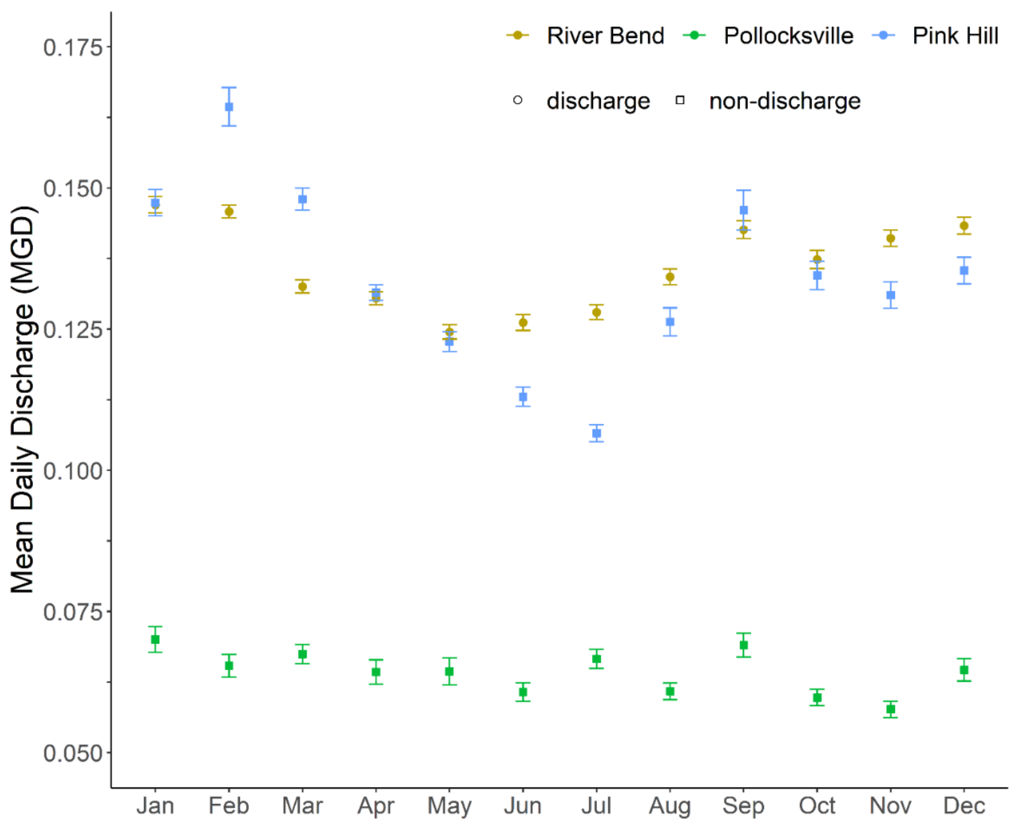

Figure 44. Mean daily discharge (million gallons per day [MGD]) from discharge and non-discharge permitted facilities. Data were reported as the mean daily discharge each month from 1997, 2002, and 2006-2021 (NC DEQ, 2023a). Discharge facilities refer to facilities that release wastewater directly to surface waters, whereas non-discharge facilities are those that land apply wastewater discharges.

Annual trends in mean daily discharge were variable across the various permitted facilities (Fig. 45). The mean daily discharge from wastewater treatment plants in Pink Hill and Pollocksville both tended to increase over time. Both municipalities have been experiencing population declines over the past decade, thus the increased mean daily discharge is not likely due to population growth (US Census, 2023). The Town of Pink Hill also received wastewater from Deep Run Sewer District (since at least 2006 but no earlier than 2002) and Duplin County (since 2017). Thus, the additional wastewater load from these communities likely contributed to the increased discharge over time. Population in the Town of River Bend has generally increased from 1990 – 2020 (US Census, 2023), yet the mean daily discharge from the wastewater treatment plant does not exhibit a clear temporal trend. The population of River Bend was approximately 3,000 in 2010 and the mean daily discharge for 2010 was 0.127 MGD, which was similar to the overall mean 0.120 MGD. The water treatment plant at River Bend exhibited tended to remain steady around 0.025 MGD. Mean daily discharge from this facility was 0.020 MGD. There was some interannual variability at this facility and the mean daily discharge ranged from 0.011 – 0.035 MGD (Fig. 45). Other factors (e.g., household water behaviors, interannual variability, inflow and infiltration [wastewater only], sewer pipe leaks [wastewater only]) may also be significant variables affecting annual variability in mean daily discharges from these facilities. Additional information is needed to assess the impact of these factors on discharges from water and wastewater treatment plants.

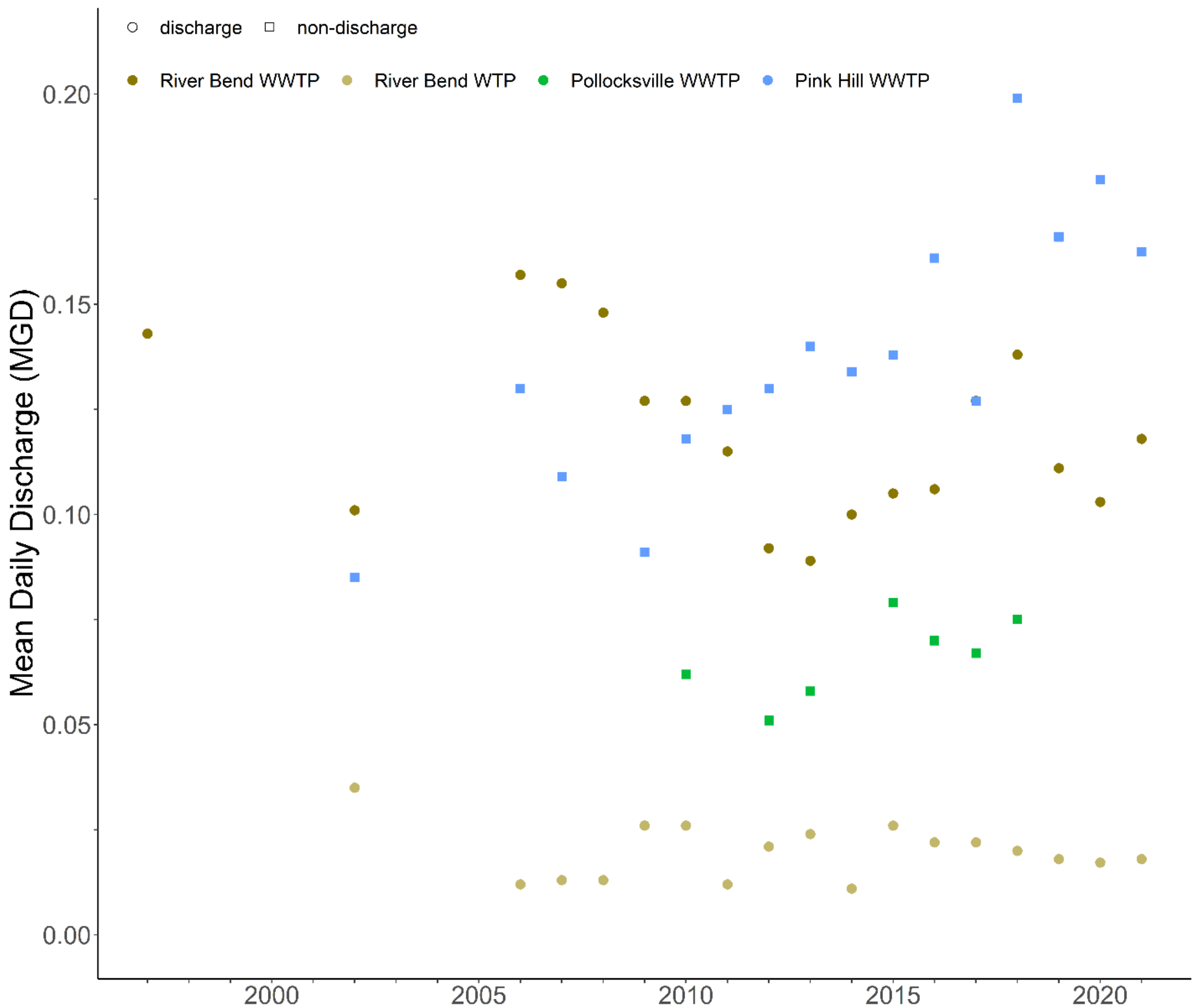

Figure 45. Mean daily discharge (million gallons per day [MGD]) from permitted discharge and non-discharge facilities. Data were reported as the mean daily discharge over an annual period from 1997, 2002, and 2006-2021 (NC DEQ, 2023a). Discharge facilities refer to facilities that release wastewater directly to surface waters, whereas non-discharge facilities are those that land apply wastewater discharges. Annual reports from some facilities did not include wastewater data. WTP= water treatment plant; WWTP= wastewater treatment plant.

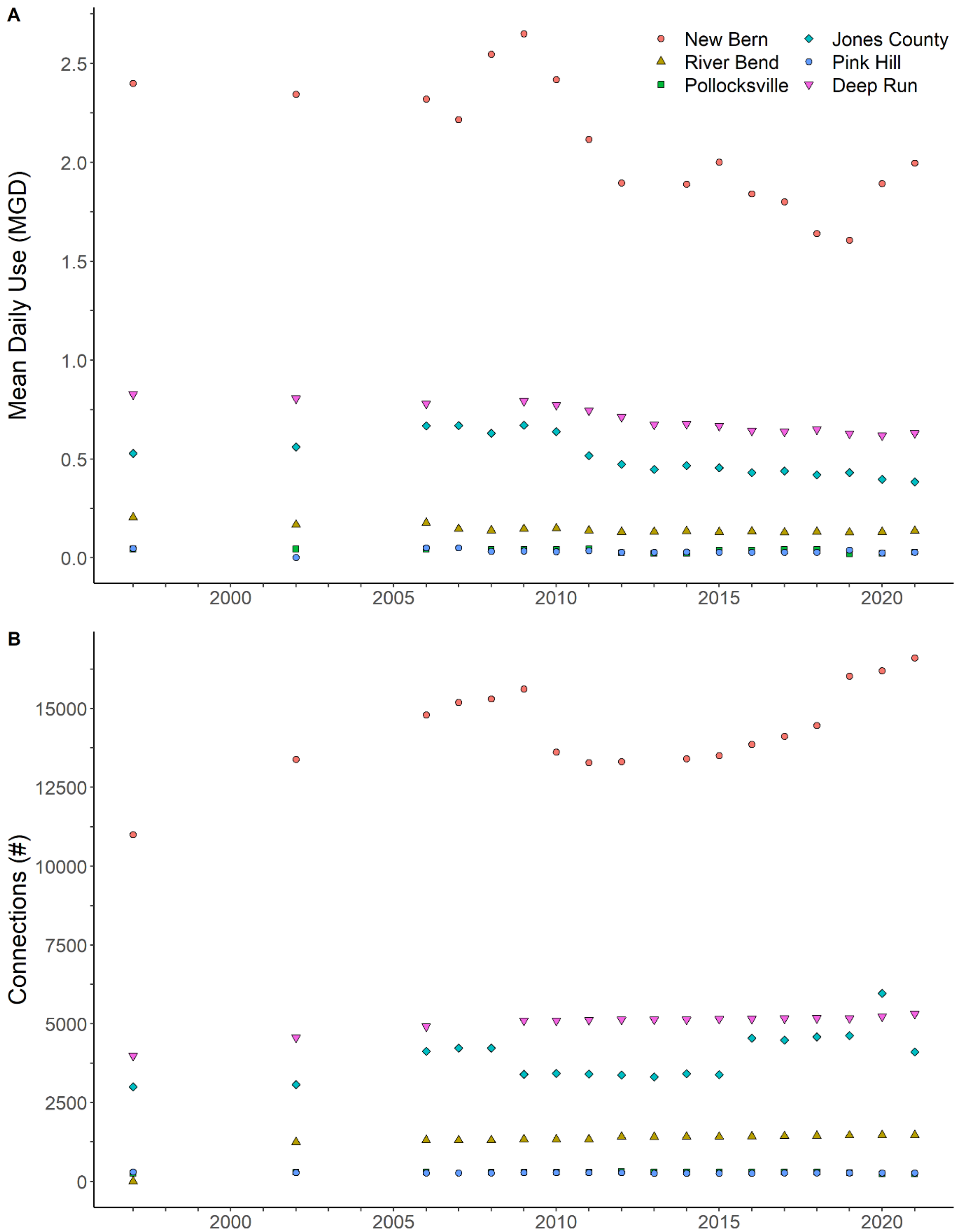

Figure 46. Time series of mean daily use (A) and number of connections (B) for residential water uses in the 6 public water supplies from 1997 - 2020. The New Bern and Deep Run Water Corporation water suppliers have groundwater wells outside of the Trent River Watershed, thus water use data includes customers outside of the studied watershed.

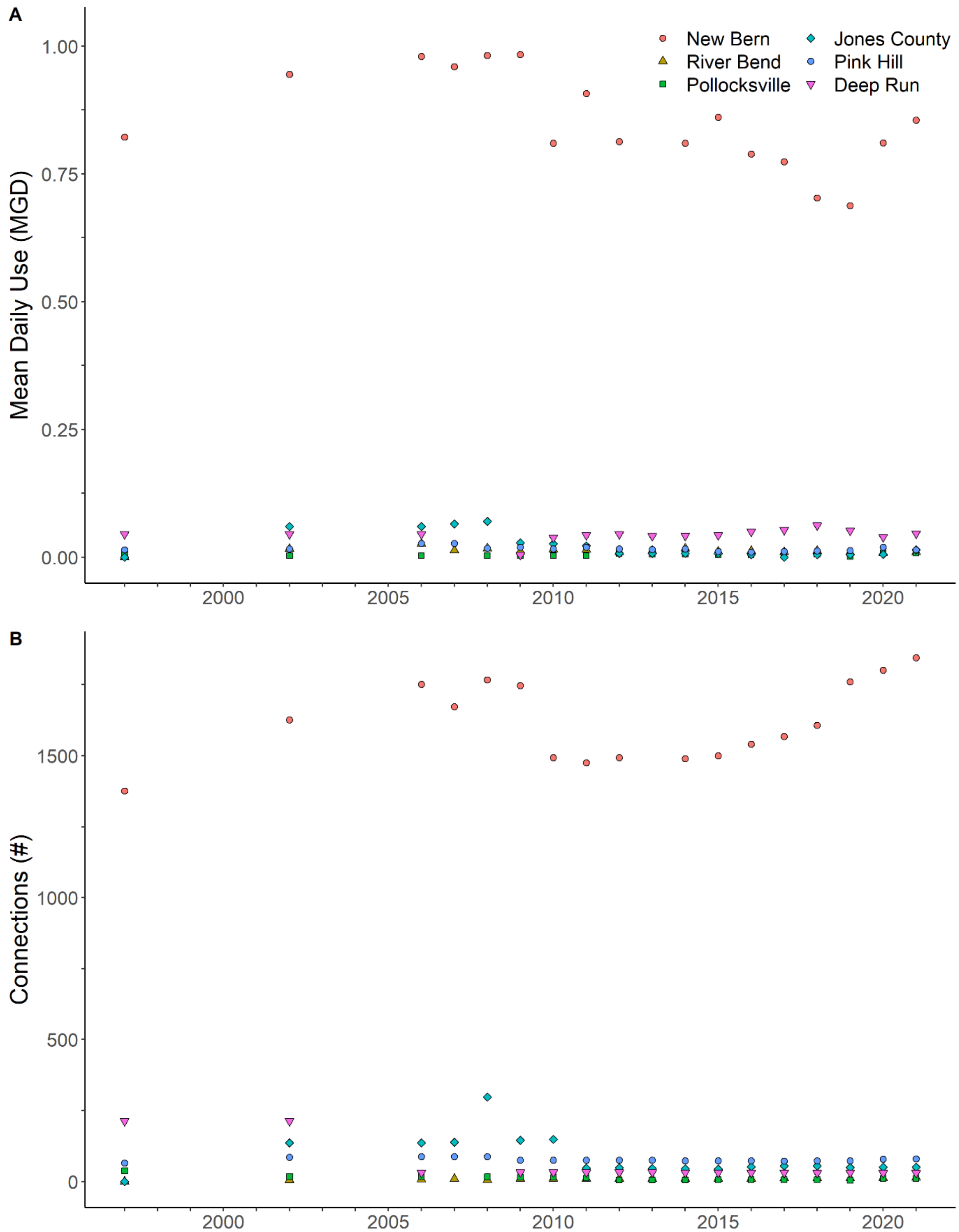

Figure 47. Time series of mean daily use (A) and number of connections (B) for commercial water uses in the 6 public water supplies from 1997 - 2020. The New Bern and Deep Run Water Corporation water suppliers have groundwater wells outside of the Trent River Watershed, thus water use data includes customers outside of the studied watershed.

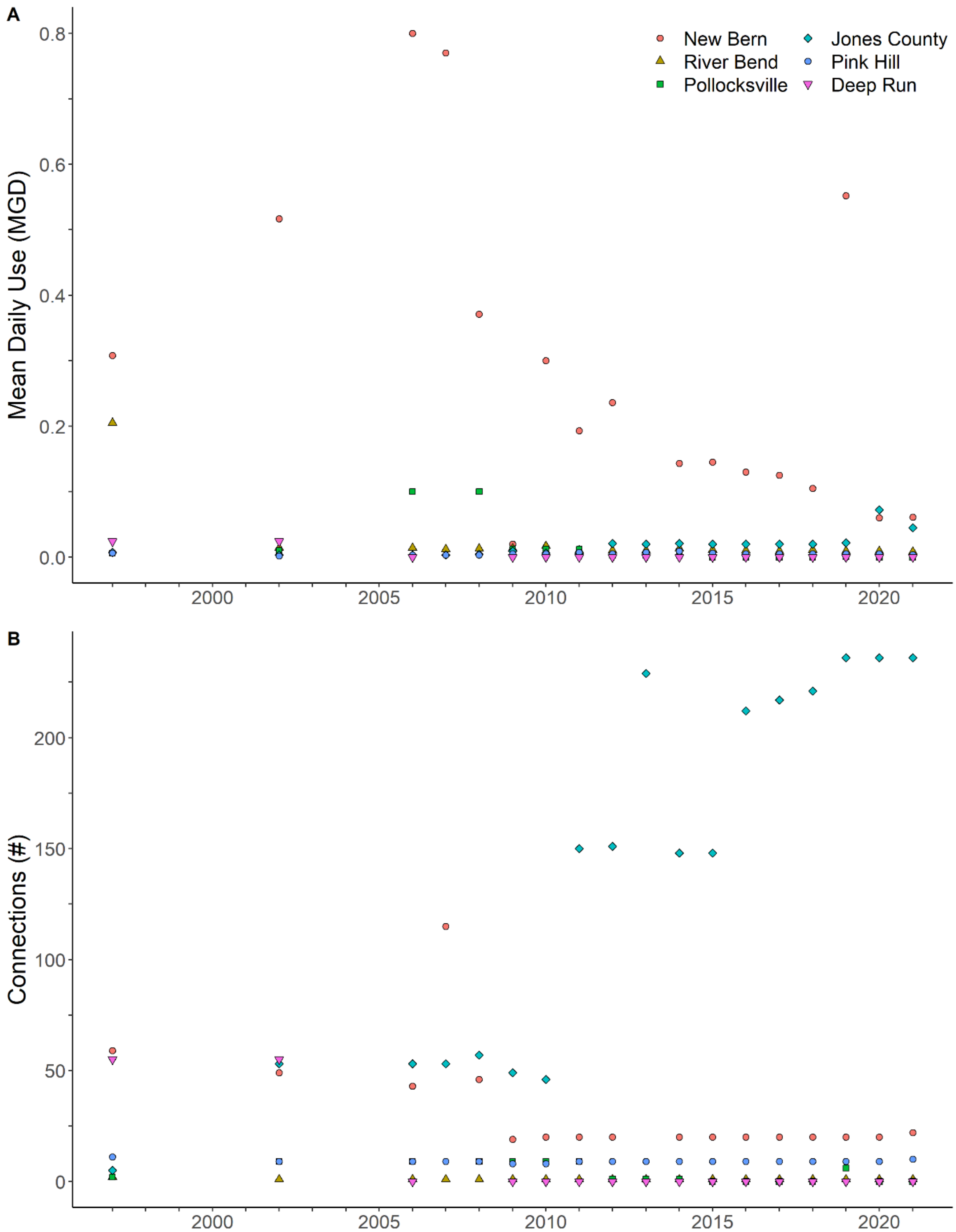

Figure 48. Time series of mean daily use (A) and number of connections (B) for industrial and institutional water uses in the 6 public water supplies from 1997 - 2020. The New Bern and Deep Run Water Corporation water suppliers have groundwater wells outside of the Trent River Watershed, thus water use data includes customers outside of the studied watershed.

Appendix C- Trent River Flow, Stage and Water Quality Data Links

Site	Site ID	NCDEQ Sites	USGS Stations	Data	Data Links
Near Trenton	A		2092500	flow, stage	https://waterdata.usgs.gov/monitoring-location/02092500/#parameterCode=00065&period=P7D
Pollocksville	D		2092554	stage	https://waterdata.usgs.gov/monitoring-location/02092554/#parameterCode=00065&period=P7D
Near Trenton	A	J8690000		SC	https://www.waterqualitydata.us/
Pollocksville	D	J8730000		SC	https://www.waterqualitydata.us/
Trent Woods Dr	F	J8770000		SC	https://www.waterqualitydata.us/
New Bern	H	J8570000		SC	https://www.waterqualitydata.us/